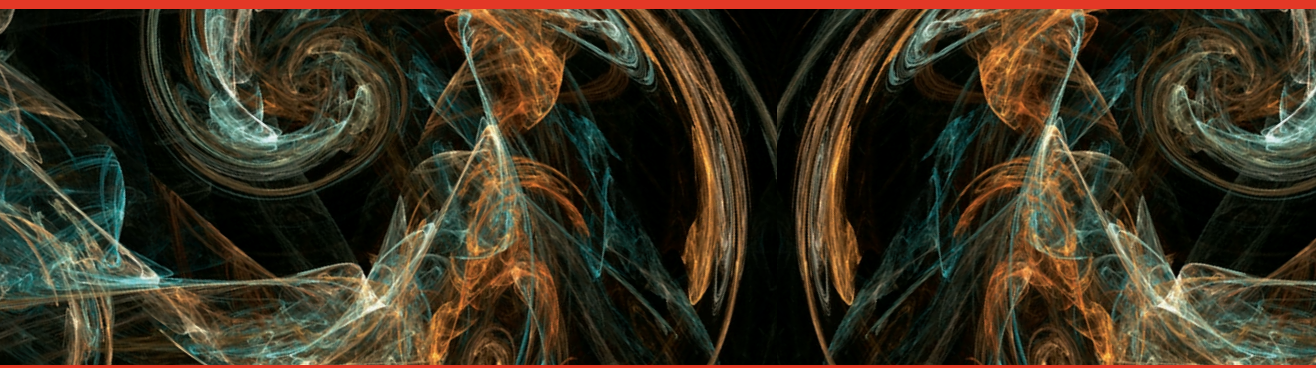
The SAGE Handbook of Complexity and Management



Edited by
Peter Allen,
Steve Maguire and
Bill McKelvey

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Contents

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Arash Azadegan is Assistant Professor of Management at New Mexico State University. His research interests include creativity and innovation across firm boundaries, as well as the effects of service and design outsourcing on performance and complexity in supply networks. He has over 10 years of combined managerial and technical experience with Quaker Oats, Ford Motor and Fortune Brands companies. His research has been published in the *Journal of Operations Management, Supply Chain Management Journal* and *International Journal of Operations and Production Management*, among others. He is also an active member of the Academy of Management and Decision Sciences Institute.

James S. Baldwin joined the Sheffield University Management School (SUMS) in January 2005 as a Lecturer in Operations and Project Management, then the Advanced Manufacturing Research Centre with Boeing as a Senior Research Fellow in 2010. He project managed a recent 3-year, £350k, research project investigating the evolution and classification of aerospace supply chains. This research, sponsored by both the ESRC and Boeing, was a collaborative project between SUMS, the AMRC with Boeing (Sheffield), the Complex Systems Management Centre, Cranfield University, and key players in the aerospace supply chain. James is currently project managing a €7.3m EU funded, series of work packages involving several European universities and industrial partners (15 in total), the main objective of which is to develop a model of a virtual factory through developing integrated models of organizations, processes and systems in a virtual environment. James has written and contributed to 70 research papers for conferences/workshops, book chapters and academic journals.

Steven C. Bankes is Chief Architect with BAE Systems Advanced Information Technologies. Dr Bankes did his undergraduate work at the California Institute of Technology, and received his PhD from the University of Colorado in Computer Science. His publications span computer science, artificial intelligence, artificial societies, operations research, policy analysis, neuroscience, machine learning, and climate studies. Dr Bankes introduced the concept of 'exploratory modeling' for decision analysis purposes based on the use of iterative computational experiments to develop information about the ensemble of plausible futures. Methods for exploratory modeling he developed were applied to robustness analysis with models, leading to robust decision methods such as Robust Adaptive Planning. That work also contributed to other policy related methods and topics including exploratory analysis, long term policy analysis, and capabilities based planning. The unifying vision behind Dr. Bankes' research has been the use of multiple models, including both ensembles of alternatives and collections of symbiotic models that can be combined opportunistically for a given purpose. Multi-model methodologies have significant implications for issues of model identification, model estimation, and uncertainty analysis. And combined with the concept of robust inference, these approaches provide a means to support practical decisions without adopting unrealistic assumptions.

Oliver Baumann is an Assistant Professor of Management at the Munich School of Management, Ludwig-Maximilians-University Munich, Germany. His research interests focus on the intersection of organization theory, strategy, and information and innovation management, with an emphasis on the strategic and organizational implications of complexity. His current research concentrates on issues related to organizational search, organizational design, and the computational modeling of firms as complex adaptive systems. He received his PhD in management from Ludwig-Maximilians-University Munich in 2008.

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Jean Boulton is Visiting Fellow with the Complex Systems Research Centre at Cranfield School of Management and Visiting Fellow with the Department of Social and Policy Sciences at the University of Bath. She designed and led the teaching of complexity theory to MBA students at Cranfield for several years and regularly teaches and writes on complexity thinking. She and Peter Allen are completing a book, Embracing Complexity, to be published by Oxford University Press in 2011. Jean has a PhD in theoretical physics, and an MBA. She is Chair of Sustain Ltd, Chair of Social Action for Health, and Director of Claremont Management Consultants Ltd. Her work focuses on strategy, organization development and community development in times of uncertainty and fast-change. Her research interests include the implications of complexity for policy makers and Pragmatism as an approach to exploring complex issues in human systems.

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Robert Chia is Professor of Management at the University of Strathclyde Business School and Emeritus Professor of Management, University of Aberdeen. He received his PhD in Organization Studies from Lancaster University and publishes regularly in the leading international journals in organization and management studies. He is the author/editor of four books and a significant number of international journal articles as well as book chapters in a variety of management sub-fields. His latest book with Robin Holt, published by Cambridge University Press in October 2009, is entitled *Strategy without Design: The Silent Efficacy of Indirect Action.* Prior to entering academia 21 years ago he worked for 16 years in Aircraft Engineering, Manufacturing Management and Human Resource Management and was a successful senior manager for a large multinational corporation based in the Asia-Pacific. His current research interests revolve around the issues of strategic leadership and foresight, complexity and creative thinking, and the impact of contrasting East-West metaphysical mindsets on executive decision-making. His overall concern is with the enhancement of life chances through understanding the general economy of effort involved in wealth creation.

Paul Cilliers is Professor of Complexity and Philosophy at Stellenbosch University, South Africa. He teaches Post-structuralism, Philosophy of Culture, Complexity and Philosophy of Science. He was born on 25 December 1956 in Vereeneging, South Africa and attended school in Germiston and studied at Stellenbosch University and at Unisa. Paul Cilliers has a degree in Electrical Engineering and a PhD in Philosophy. He worked as a research engineer for over a decade, specializing in computer modelling and pattern recognition using neural networks. After completing his doctorate (supervised by Johan Degenaar of Stellenbosch and Mary Hesse of Cambridge), he was appointed to the Philosophy Department of Stellenbosch University. He teaches mainly cultural philosophy and deconstruction, as well as giving courses in the philosophy and ethics of science. His current research focuses on the philosophical implications of complexity theory. In *Complexity and Postmodernism* he introduces complexity theory from a philosophical perspective, and argues for certain similarities between complexity and the post-structural positions of Derrida and Lyotard. The aim of this comparison is to tone down some of the exaggerated claims made in the name of Derrida and others, but also to show that complex problems will not be solved by general, analytic and abstract means. In 2000 he was given the Rector's Award for Excellence in Research, and in 2006 was awarded the prestigious Harry Oppenheimer Fellowship.

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Kathleen M. Eisenhardt is the S.W. Ascherman Professor in the School of Engineering at Stanford University and co-director of Stanford Technology Ventures Program. Eisenhardt's research focuses on high-velocity markets and technology-based firms. She is now studying innovation collaborations across firms, strategy as simple rules, and competitive interaction. She is a co-author of *Competing on the Edge: Strategy as Structured Chaos* which emphasizes the implications of complexity theory for strategy. Her most recent publication on complexity theory is titled 'Optimal Structure, Market Dynamism, and the Strategy of Simple Rules' (co-authored with Jason Davis and Christopher Bingham) and appeared in *Administrative Science Quarterly* in 2009. Her next complexity publication is on simple rules as rational heuristics (with Christopher Bingham), forthcoming in *Strategic Management Journal*.

Glenda Eoyang is founding Executive Director of the Human Systems Dynamics Institute and its network of Associates; Director and faculty member of the Center for Human Systems Dynamics at The University of St Thomas in Minnesota; an associate of the Center for Evaluation, Planning, and Assessment at Queen's University in Kingston, Ontario, Canada; Scientific Advisor to the Plexus Institute; member of the Circle of Scholars of The Union Institute and University; and recipient of the Organization Development Network's *Sharing the Wealth Award* (2009). As a pioneer in the field of human systems dynamics, she applies principles of self-organizing systems to help people thrive in unpredictable environments. Since 1988, she has provided training, consulting, coaching, research, evaluation, and facilitation for complex change in public and private sectors. Her approach to systems thinking focuses on a lively integration of theory and practice as she helps people see and influence patterns that emerge within and around individuals, teams, organizations and communities. Current projects reflect her passion for effective complex change: prevention of child abuse and neglect, complex dynamics of conflict and peace, integrated and equitable human services, evaluation of systemic change, and adaptive action to replace strategic planning in times of chaos and uncertainty. Her published works include *Coping with Chaos: Seven Simple Tools* (Lagumo, 1996), *Facilitating Organization Change: Lessons from Complexity Science* with Ed Olson (Jossey-Bass/Pfeiffer, 2003), and *Voices from the Field: An Introduction to Human Systems Dynamics* (HSD Press, 2003) an edited collection of stories about how practitioners apply human systems dynamics in various contexts.

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Steve Maguire is Associate Professor of Strategy and Organization in the Desautels Faculty of Management at McGill University in Montreal, Canada. He received his Ph.D. from HEC-Montreal in 2000, after spending a month at the Santa Fe Institute in their Complex Systems Summer School. He has co-edited a special issue [1999, 1(2)] of *Emergence* devoted to "Complexity and Management"; and co-authored a comprehensive review chapter addressing the same topic for the 2006 *SAGE Handbook of Organization Studies.* His empirical research focuses on institutional, technological and organizational change resulting when commercial, scientific and political struggles intersect around social or environmental issues. For example, his doctoral dissertation draws lessons from society's experience with the insecticide DDT and was awarded the Academy of Management's "Organization and Natural Environment (ONE)" Best Doctoral Dissertation Award in 2001. He has also studied the pharmaceutical sector, analyzing the impact of the empowerment of people living with HIV/AIDS on the commercialization, availability and accessibility of treatments. His research has appeared in the *Academy of Management Journal*, *Emergence, Global Governance, Greener Management International*, *Health Care Management Review*, *Journal of Management Studies, Organization Studies*, and *Strategic Organization.*

Russ Marion (Clemson University) is author of the books, *The Edge of Organization* (1999) and *Leadership in Education* (2001); co-editor of the book, *Complexity Leadership*; editor of a special issue of *The Leadership Quarterly* on leadership and complexity; and author of numerous articles on leadership, including one that was honoured in 2001 as best paper of the year by *The Leadership Quarterly* and the Center for Creative Leadership. He co-organized workshops on complexity leadership at the Center for Creative Leadership and at George Washington University. He has also presented on complexity leadership at the India Institute of Technology, the Institute for Management Development in Switzerland, in workshops on destructing complex movements at the US Department of Defense, and in a number of conference venues.

Bill McKelvey—PhD MIT 1967. Professor of Strategic Organizing and Complexity Science at the UCLA Anderson School of Management. His book, *Organizational Systematics* (1982) remains the definitive treatment of organizational taxonomy and evolutionary theory. He chaired the building committee that produced the $110,000,000 Anderson Complex at

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Paul Ormerod is an economist and author of three best selling books, *The Death of Economics*, *Butterfly Economics* and *Why Most Things Fail*, a Business Week US Business Book of the Year. He writes extensively on economic, social and cultural issues and publishes in a wide range of academic journals, such as *Physica A, Proceedings of the National Academy of Science, Social Science and Medicine, Journal of Artificial Societies and Social Simulation, Cultural Science, Diplomacy and Statecraft,* and *Economics e-Journal*. In 2009 he was awarded an honorary DSc by the University of Durham for his innovative contributions to economics. His website is www.paulormerod.com. Paul read economics at Cambridge and took the MPhil in economics at Oxford. He started his career as a macroeconomic modeler and forecaster at the National Institute of Economic and Social Research. In the early 1980s he moved to be Director of Economics at the Henley Centre for Forecasting, and sold it to Martin Sorrell's WPP Group Plc in the mid 1990s. He is a director of Volterra, which he founded in 1998.

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Complexity and Management: Introducing the *SAGE Handbook*

Steve Maguire, Peter Allen and Bill McKelvey

Complexity is one of the fastest growing topics of research in the natural and social sciences. A new, transdisciplinary and paradigm-shifting science of complexity is emerging at the interstices between a diverse set of disciplines, challenging traditional disciplinary assumptions and boundaries. In the field of management and organization studies, the application of complexity science has grown dramatically over the past two decades: numerous scholarly as well as practitioner-targeted books have been written; many special issues of journals have been published; several new specialized journals have been created; and articles applying complexity science to organizational phenomena are now regularly appearing in leading management journals. Additionally, a complexity perspective is increasingly being taken up by practitioners in business, government and non-government organizations. These exciting developments – their cumulative effect and the range of management subdisciplines affected – motivate this volume: the *SAGE Handbook of Complexity and Management*.

The time has come for taking stock of, and reflecting upon, how complexity science has influenced management and organization studies over the past two decades; and for suggesting future directions for integrating complexity science into the production of knowledge about and relevant for contemporary management. This *Handbook* critically reviews, juxtaposes and organizes the growing body of research at the intersection of complexity and management – work which addresses the implications of complexity science for the epistemological and methodological *foundations* of management knowledge; *applications* of complexity science concepts, theories and models to important management issues and in different organizational contexts; and theoretical developments at key *interfaces* emerging between management and adjacent disciplines. Written by internationally respected scholars, the *Handbook* seeks to bring cohesion to a collection of seemingly disparate approaches; to provide readers with a clear overview of a heterogeneous field; and to set the stage for future scholarship that is of value to managers and to society.

In this introduction we provide a brief overview of the field emerging at the intersection of complexity and management; and situate it in a specific historical and conceptual context within organization studies.

We then introduce the various *Handbook* chapters, and conclude with a discussion of the significance of complexity science for management scholarship as well as suggestions for future research.

THE INTERSECTION OF COMPLEXITY AND MANAGEMENT

For several decades now, complex systems have received substantial attention in a range of disciplines and from this has emerged a broad and interdisciplinary complexity science (see Allen, 1981, 1988, 1990; Prigogine and Stengers, 1984; Anderson et al., 1988; Nicolis and Prigogine, 1989; Lewin, 1992; Waldrop, 1992; Wheatley, 1992; Kauffman, 1993; Casti, 1994; Mainzer, 1994; Bar-Yam, 1997). A complex system is a 'whole' made up of a large number of interacting 'parts', or 'agents', which are each governed by some rule or force which relates their behaviour in a given time period contingently to the states of other parts. Interactions among parts are usually though not necessarily local and rich; and can be material or informational. As individual parts respond to their own specific local contexts in parallel with other parts, qualitatively distinct emergent patterns, properties and phenomena can arise at the level of the system despite the absence of explicit inter-part coordination. Outcomes of this process of upward causality are very difficult to predict from knowledge of the parts and rules however. In addition, once emergent phenomena exist, they can in turn exert downward causality on the parts through the same rules that brought them into existence. 'Complexity' arises when emergent system-level phenomena display patterns in time and space that are neither static nor random but are, rather, difficult to describe parsimoniously.

Complexity science is the systematic study of complex systems as well as the phenomena of emergence and complexity to which they give rise. It has generated a set of concepts that is almost mathematical in its abstractness and potential applicability to a range of empirical phenomena in which large numbers of parts interact richly over time – from spin glasses to immune systems to ecosystems to economies.

The idea of viewing natural and social systems as complex adaptive ones – of taking seriously their status as evolving products of evolution – constitutes a major revolution in thinking which will have impacts on society as great as those of the Enlightenment, when reason and rationality led to the development of much of modern society and classical science. Complexity science challenges not only the foundations of our knowledge – our philosophy and our science – but also the economic, political and social institutions we build upon that knowledge.

The new vision afforded by the development of complexity science forces us to confront the idea that managerial and organizational knowledge pertaining to actions and policies in evolved – and evolving – social systems is necessarily limited and incomplete instead of being based on objective truth about eternal natural laws governing unchanging systems. We may be able to describe and analyse organizational dynamics within natural and social systems, but this description will have to reflect the facts that part of the experience of any agent is the interaction with others and that these agents will in general have different perspectives and views on reality. The values, aims and goals of different actors will not necessarily coincide and the trajectory of the system will therefore express both the mutual reinforcements and conflicts of these. Not only this, but over time as agents and actors experience the outcomes of their beliefs and behaviours, they will sometimes feel them confirmed and other times revise and change them, leading to new system behaviour and responses.

Although it may be possible to predict some features of a system under some conditions, sometimes seemingly small and inconsequential local events in a system can be amplified to cause global change. A complexity perspective thus provides a scientifically grounded basis for accepting two paradoxical forms of wisdom. Individuals can change their worlds through their interventions, but their agency must be reflexive and respectful of the complexity of the system in which they are embedded. Both the dream of omnipotence and the nightmare of impotence in a fully knowable but deterministic world dissolve with complexity science, which in many ways represents an important cultural awakening.

Adopting a complexity perspective has important ontological, epistemological and axiological implications with which management researchers and practitioners alike must come to terms. Complexity science not only offers a new view of the world, but also new methods for studying and generating knowledge about it. By going beyond simple assumptions of evolution and change necessarily meaning 'progress', or of 'good' management having a self-evident, unequivocal definition, we must examine more critically questions of responsibility, accountability and governance, and potentially change management education in consequence. Thus does complexity science shake and re-anchor the foundations of descriptive and normative knowledge within the discipline of management and beyond. With its trans-disciplinary roots and appeal, a complexity perspective also opens up promising avenues of interface between organization studies and other related disciplines where complexity science is already transforming conventional thinking, such as economics, sociology, geography, and – importantly in our current era – ecology and environmental studies.

This new scientific approach not only embraces dynamics instead of the 'statics' of equilibrium, but goes beyond investigation of the mere 'running' of a given dynamical system according to fixed rules: it accepts and anticipates system plasticity (i.e. the appearance of qualitatively new features and disappearance of old ones). It embraces evolution: the emergence and qualitative development of structure and organization. Complexity is the science of organization – and in particular its origin and evolution – and is therefore the natural framework for considering organization and connected entities. Indeed, whereas classical science considered an ontology of isolated objects, complexity science considers an ontology of connected entities, i.e. a network which has links that change, nodes that change internally, and capabilities that develop and change over time. Complexity scholars also confront the fact that neither the modeller nor the model are outside the system modelled, but instead are part of it, such that both building and running the model can lead to changed behaviour on the part of the modelled and the modeller. Clearly, in efforts such as 'climate change modelling' this process is already evident and inescapably political, since the object of the modelling is to establish 'facts' about possible futures so that changes in behaviour will take the system down a more benign pathway than otherwise. CEOs and other managers face a similar situation inside organizations – their representations and interventions change the organization they are managing.

Complexity science therefore provides scholars with a firm and scientifically anchored foundation from which to explore and understand human organizations.

COMPLEXITY AND MANAGEMENT: LOOKING BACK

While complexity science and the use of complex adaptive systems to model organizational phenomena is in some ways revolutionary, it is important to underline that systems approaches to understanding organizations and the construct of complexity each have long and respected heritages within management and organization studies. Indeed, Reed (1985) argues that systems theorists dominated management and organization theory from the 1930s to the 1970s; while Scott's (2002) discussion of organizations from 'rational, natural and open systems perspectives' appears to have become canonical, with a fifth edition released in 2002 and a sixth co-authored edition following in 2007 (Scott and Davis, 2007).

As early as Barnard (1938), organizations were conceptualized as 'cooperative systems' from which emerged novel organization-level properties (i.e. qualitatively new features, distinct from those of the organizational members whose coordination gave rise to them). Following this, researchers elaborated 'general systems theory' (e.g. Von Bertalanffy, 1950, 1968; Boulding, 1956), from which came a series of important contributions to understanding organizations as systems, such as Ashby's (1956) 'Law of Requisite Variety'; Simon's (1962) description of the 'architecture of complexity', derived from research into information-processing and decision making in complex organizations; Katz and Kahn's (1966) characterization of organizations as 'open systems'; and Thompson's (1967) exploration of 'organizations in action', now recognized as foundational to the development of structural contingency theory.

The construct of complexity is important in contingency theory as a variable used to characterize the structure of organizations and of their environments (Hall et al. 1967; Anderson 1999). Extant research advocates viewing the complexity of a given organization as proportional to the number of organizational subsystems involved in information-processing and measuring complexity using three dimensions: vertical (e.g. number of hierarchical levels in an organizational structure); horizontal (e.g. number of different units at a given level); and geographic (e.g. number of distinct operational sites; see Daft, 1992). In a similar line of thinking – and, related through Ashby's Law of Requisite Variety – extant research also recommends measuring the complexity of a given organizational environment by the number of entities in it to which an organization must pay attention (Scott, 2002; Boisot and McKelvey, 2010).

This line of inquiry tends to view organizations from outside and with an objectivist epistemological stance, such that organizations are seen in terms of the information-processing they carry out. But systems approaches are also compatible with inquiry from an interpretivist epistemological stance and adopting the 'action frame of reference' (Silverman, 1970) of actors inside organizations. The contributions of Checkland (1981), who builds upon and extends Vickers' (1965) notion of an appreciative system in his development of 'soft systems thinking' and associated methodologies, exemplify this approach. Recognizing that actors' interpretations of the situations they face – *in situ* – are integral components of any organizational system, the meanings attributed to organizational events, as both causes and consequences of actions, thus become important sites for research and for managerial interventions to bring about change. Similarly, Daft and Weick (1984: 284) begin with the premise 'that organizations are open systems that process information from the environment but then highlight that the environment may not be analyzable and, in any case, can be intruded upon, shaped and ultimately enacted, which leads them to characterize organizations as 'interpretation systems'.

It was into this scholarly context that ideas from what would eventually be termed complexity science began to be introduced in the 1980s. A recent review of the field of complexity and management (Maguire et al., 2006) identified a sequenced movement of complexity concepts into organization studies: self-organization, dissipative structures and order out of stochastic chaos appeared earliest; then deterministic chaos was attended to; finally, complexity science described as such was discussed. This more or less parallels the appearance of books popularizing these topics for a general audience, including Jantsch's (1980) account of the 'self-organizing universe'; Prigogine and Stenger's (1984) depiction of 'order out of chaos' and dissipative structures; Gleick's (1987) introduction of deterministic chaos; Lewin's (1992) description of complexity and 'the edge of chaos'; and Waldrop's (1992) journalistic account of the earliest days of a self-conscious science of complexity and the founding of the Santa Fe Institute.

Perhaps the first link between 'management' and complexity arose in the field of 'natural resource management'. Problems of forest and fishery management were important and active domains in great need of successful management. Major progress was made in ecological management when the idea that management of natural resources needed to be seen as a learning process. Adaptive resource management (ARM) is a structured, iterative process of decision making in the face of uncertainty, with the aim of reducing uncertainty over time via system monitoring. In this way, management is guided essentially by 'learning by doing' and pragmatism which accepts the reality of complexity and the consequent limits to knowledge (Holling, 1986). Another example was more direct when complex systems models of Canadian fisheries were developed in order to improve their management (Allen and McGlade, 1986; 1987). These provided a practical and real demonstration of the importance of understanding management as the successful interworking of two almost opposite behavioural patterns – those of discovery and exploitation. The first required a willingness to sail into the unknown, ignoring current rational choices, whereas the second required making optimal use of existing information. These ideas appeared again, recast by March as general problems of managing and organizing in his famous paper on 'exploration and exploitation' (March, 1991). In many ways all of this work can be seen as the development of Herbert Simon's pioneering ideas – in the real world the behaviour of agents was not that of full rationality, assuming access to total information, but was that of 'bounded rationality' governed by what agents (or actors) considered to be 'sufficient' information, resulting in what Simon called 'satisficing' not maximizing behaviour. This was a very important insight that helped open the path to complexity science (Simon, 1982).

In the mid-1980s several groundbreaking studies took seriously the idea that organizations could be understood and modelled as ongoing processes that were far from, rather than at, equilibrium. For instance, Gemmill and Smith (1985) presented a model of organizational transformation which drew upon the concept of dissipative structure; Goldstein (1988) presented a far-from-equilibrium approach to resistance to change; while Morgan's (1986) celebrated book, *Images of Organization*, addressed 'self-organization' and 'autopoiesis'. In a related development, organizational scholars also posited a constructive role for disorder, or 'chaos' in the non-mathematical sense: Quinn (1985) suggested that the management of innovation required 'controlled chaos'; Peters (1987) prescribed 'thriving on chaos'; while Nonaka (1988: 72) asserted that 'the self-renewal strategy of an organization lies in its ability to manage the continuous dissolution and creation of organizational order'. Paradoxically, despite importing 'hard science' concepts seemingly more compatible with an information-processing approach to organizations, this work also tended to prescriptions that called for more managerial attention to 'soft science' concepts of interpreting, sense-making and constructing meanings.

In seeing disorder, uncertainty and crisis in a positive light, this work questioned not only the merits but also the feasibility of centralized management of organizational processes; top-down control was proving to be, in the long term, dysfunctional to organizations. Authors accordingly prescribed decentralization of decision making and more autonomy and empowerment for workers (i.e. distributing control among members of a more autonomous workforce). This emphasis on embracing disequilibrium and distributed control continued in the 1990s as scholars translated the so-called 'new sciences' (Wheatley, 1992) into organizational terms and drew lessons for managers. For example, Stacey (1992, 1993) conceptualized strategy as 'order emerging from chaos' and counselled managers to abandon stability and harmony as objectives; rather, successful organizations welcomed uncertainty, actively promoted instability of a sort and channelled resulting tensions and conflicts in beneficial ways. Unpredicted deviations from routines – analogous to the 'fluctuations' which lead to Prigogine's dissipative structures – should be amplified rather than dampened to bring about organizational renewal (Goldstein, 1994). Instead of seeking to eliminate uncertainty, or at minimum buffering the organization's core operations from it – long viewed as a key function of management, in accordance with contingency theory (Thompson, 1967) – managers were advised to recognize the benefits of 'coping with uncertainty' and to embrace its transformational possibilities (Merry, 1995).

Throughout the 1990s and into the following decade, much of the literature addressing complexity and management was devoted to what Maguire et al. (2006) refer to as 'introductions' of complexity science (as well as related topics such as chaos theory and non-linear dynamics). This work, summarized in Table 1.1, introduced natural science approaches to complex systems (typically optimistically) to management scholars; argued (typically enthusiastically) for the applicability of these approaches to organization studies or some sub-discipline within it; and described implications (typically profound) of applying the science of complexity to organizations. Some of this work also introduced mathematical formalisms and computational methods associated with complexity science (e.g. Anderson, 1999); or discussed possible limitations of complexity science methods as applied to organizations (e.g. Johnston and Burton, 1994; Cohen, 1999).

The vast majority of this work was descriptive, presenting complexity science terminology and stylized facts about complex systems but rarely developing formal theories or models; for notable exceptions, see Drazin and Sandelands (1992), Levy (1994), Stacey (1995), Thietart and Forgues (1995), and Morel and Ramanujam (1999). Similarly, although examples and illustrations were invoked – typically to underline the similarities between organizational phenomena and characteristic features of other types of complex systems – these often relied on argument by analogy or resemblance thinking; and empirical studies were rare. Nonetheless, it brought complexity science ideas to the management and organizational research community.

Special issues of journals also played an important role in introducing complexity science to management scholars, as evidenced by this list (which is illustrative and not intended to be exhaustive):

- *Human Systems Management* (1990, Vol. 9.4) on 'Chaos and self-organization in companies'
- *Journal of Management Inquiry* (1994, Vol. 3.4) on 'Chaos and complexity'
- *Organization Science* (1999, Vol. 10.3) on 'Applications of complexity theory to organization science'
- *Management Communication Quarterly* (1999, Vol. 13.1) on 'Dialogues of self-organizing'
- *Health Care Management Review* (2000, Vol. 25.1) on 'Chaos and complexity theory for health care management'
- *Journal of Organizational Change Management* (2000, Vol. 13.6) on 'Change, emergence and complexity theory'
- *Research Policy* (2000, Vol. 29.7–8) on 'Complexity and innovation'
- *The Learning Organization* (2003, Vol. 10.6; 2004, Vol. 11.6) on 'Chaos, complexity and organizational learning'
- *Management Decision* (2006, Vol. 44.7) on 'The application of complexity science to business'
- *Public Management Review* (2008, Vol. 10.3) on 'Complexity theory and public management'.

Accompanying this work targeting management academics was the publication of a large number of books for management practitioners, leading some scholars to worry that complexity was becoming just another management 'fad' (McKelvey, 1999b). This concern, which also stemmed from the highly metaphorical content of much of this practitioner-targeted work, prompted an innovative special issue of *Emergence* (1999, Vol. 1.2), the first journal devoted to complexity science and organization studies (and since

Table 1.1 Research introducing complexity science and drawing implications for management*

Reference	*Introduction of*	*Implications drawn for*
Allen and McGlade (1986, 1987)	Evolutionary systems modelling	Natural resource management
Kiel (1989)	Non-equilibrium theory	Public administration
Priesmeyer and Baik (1989)	Chaos	Planning
Daneke (1990)	Advanced systems theory	Public administration
Zuijderhoudt (1990)	Chaos and self-organization	Organizational structure
Kiel (1991)	Nonlinear paradigm of dissipative structures	Social sciences
March (1991)	Complex systems modelling	Management
Smilor and Feeser (1991)	Chaos	Entrepreneurial processes
Reed and Harvey (1992)	Complexity; new science	Realist social science
Drazin and Sandelands (1992)	Autogenesis; self-organizing systems theory	Organizing
Gregersen and Sailer (1993)	Chaos theory	Social science research
Begun (1994)	Chaos and complexity theory	Organization science
Johnson and Burton (1994)	Chaos and complexity theory	Management
Levy (1994)	Chaos theory	Strategy
Dooley et al. (1995)	Chaos and complexity	Total quality management
Smith (1995)	Chaos	Social science
Stacey (1995)	Complexity	Strategic change processes
Stumpf (1995)	New science theories	Leadership development
Thietart and Forgues (1995)	Chaos theory	Organization
Glass (1996)	Chaos; nonlinear systems	Day-to-day management
Overman (1996)	Chaos and quantum theory	Administration
Wheatley and Kellner-Rogers (1996)	Chaos and complexity	Organizations
Lissack (1997)	Chaos and complexity	Management
McDaniel (1997)	Chaos and quantum theory	Strategic leadership
Mendenhall et al. (1998)	Nonlinear dynamics	International human resources management
Anderson (1999)	Complexity theory	Organization science
Cohen (1999)	Complex systems theories	Study of organization
Morel and Ramanujam (1999)	Complex systems theory	Organization theory
Mathews et al. (1999)	Complexity sciences	Social sciences
Duffy (2000)	Chaos theory	Career-plateaued worker
Arndt and Bigelow (2000)	Chaos and complexity theory	Health services management
Colbert (2004)	Complexity (with resource-based view)	Strategic human resource management

* Adapted from Maguire et al. (2006).

reconstituted and renamed as *Emergence: Complexity and Organization; E:CO*), which was made up of 55 reviews of 34 books by 49 different scholars. Arguing for 'moving from fad to firm foundations' to underpin the emerging field of complexity and management, Maguire and McKelvey (1999: 5) acknowledged that metaphorical applications of complexity science were indeed generating insights, but cautioned that metaphors need to be deployed explicitly as such rather than unreflexively accepted as valid alternative organizational ontologies.

In a parallel development, computational models associated with complexity science also became more common in management research. The appearance of the journal *Computational and Mathematical Organization Theory (CMOT)* in 1995 evidences this shift. As Maguire and McKelvey (1999: 42) note, 'complexity science and computational modelling go hand in hand' because assumptions of stochastically idiosyncratic agents and nonlinear interactions among a large number of variables are more easily accommodated in computational as compared to mathematical models. Among computational approaches imported into management from complexity science, Kauffman's (1993) *NK* 'fitness landscape' model was one of the earliest and most prominent ones (Levinthal, 1997; McKelvey, 1999a; Rivkin, 2000).

COMPLEXITY AND MANAGEMENT: LOOKING AT THE *HANDBOOK*

Today, even a cursory look around at the growing body of work which applies complexity science concepts, insights and models to organizational phenomena reveals incredible diversity in terms of ontological and epistemological assumptions, levels of analysis, focal phenomena theorized, complexity science concepts harnessed, research methods used, and so on. Hence a dilemma arose for this volume: what is the best way to organize this work? Actually, in carrying out the project, reflecting on complexity and reading other scholars' contributions, the dilemma was diminished somewhat: it became clear that there is no single best way of approaching complexity which, by its very nature, is constituted by competing descriptions from multiple perspectives. So, rather, what is a *useful* way to organize the work in this field? Although the number of review articles and reflections on the field to date is not large, what does exist suggests that scholars have had different answers to this question.

Maguire and McKelvey (1999), for example, distinguish between information-processing and interpretive approaches to complexity within organization studies, while Contractor (1999) notes that 'self-organizing systems research in the social sciences', identifies two programmes in tension with each other – one emphasizing 'metaphors' and the other emphasizing 'models' – and argues for reconciling the two. Similarly, Richardson and Cilliers (2001) ask the question 'what is complexity science?' and approach it from different directions as they introduce a series of answers from authors contributing to a special issue of *Emergence*. They argue that most work can be associated with one of two 'communities' – 'reductionist' hard science or 'metaphorical' soft science – before advocating the development of a third – 'complexity thinking' – which was less well represented in the work they reviewed. This community would embrace methodological pluralism (i.e. both narrative and computational or mathematical methods) and explicitly recognize limits to knowledge about complex phenomena.

Other reviews have parsed work according to its scope or level of analysis. Focusing on 'applications and limitations of complexity theory in organization theory and strategy', Levy (2000) implicitly adopts analytical scope as an organizing tool in describing more generalized models of 'economic and social systems' in a different section than models of 'firms and industries', which focus more specifically on competitive dynamics. He also addresses metaphorical applications. Similarly, but paying less attention to metaphors in favour of models, the review chapters in Baum (2002) address three distinct levels of analysis: intraorganizational complexity and computation (Carley, 2002); organizational complexity and computation (Eisenhardt and Bhatia 2002); and interorganizational complexity and computation (Sorenson, 2002).

Maguire et al. (2006) distinguish between 'objectivist' approaches, which tend to examine complex systems from outside (i.e. 'God's eye view'; Hendrickx, 1999) through models; and 'interpretivist' approaches, which tend to examine complex systems from the perspective of actors inside them through meanings. They note that not all interpretive work is metaphorical; and that the best metaphorical work uses metaphor as a tool and does so consciously (i.e. it is reflexive about the metaphorical status of inferences and insights). Their comprehensive review also pays tribute to the surprisingly large body of organizational scholarship, both objectivist and interpretivist, which attends to the implications of complexity science for ontological assumptions, epistemological considerations and research methods. They distinguish this work addressing the 'foundations' of organizational knowledge from 'applications' of complexity science to organizational phenomena.

The approach taken in this *Handbook* is most informed by the review chapter of Maguire et al. (2006) insomuch as the distinction between 'philosophy-driven' work on knowledge foundations and 'phenomenon-driven' applications is retained, but differs in several respects. First, to these two clusters of work is added a third – interfaces – which captures theoretical developments at the intersection of management and several adjacent fields. As you will see, very interesting work is being done there. Second, the objectivist–interpretivist division is abandoned in favour of a series of more specific topics which correspond more closely to various sub-fields within management and organization studies, in order to facilitate more targeted reading by scholars in the various sub-fields and perhaps new to complexity science. As you will also see, the range of topics covered spans many of the functional areas one might find in a business school, including operations, human resource management, leadership, entrepreneurship and strategy. In adopting this approach, no *a priori* stance is taken as regards the status of metaphors or different levels of analysis: contributing authors were free to deal with these as they saw fit. As you will see, metaphors play a bigger role in some chapters than others and are sometimes praised and sometimes criticized, while different levels of analysis figure more prominently in some chapters than others.

It is important to note that the approach taken makes for a unique and novel *Handbook* because of the differential penetration and integration of complexity science into various sub-fields. Where the existing body of work is of more substantial size, authors' chapters organize the literature, critically review it, and suggest future directions for research, as would be expected for typical handbook chapters. Where the existing body of work applying complexity science to a particular topic is less voluminous, however, authors have had more liberty, after reviewing the literature, to present and develop specific ideas in more depth.

Foundations

This first section of the *Handbook* addresses the underlying basis of complexity science, describing its origins and development from different domains and disciplines; introducing key concepts; and discussing the implications of complexity for epistemology and methodology. As a source of possible representations for organizations, as well as for social systems more generally, complexity science offers an abundance of flexible concepts and robust methods on which organizational scholars draw. It has also stimulated philosophical reflection, inspiring scholars to reconsider questions of what can be known and how, as well as the thorny issue of limits to knowledge. The chapters in this opening section, therefore, have been assembled such that they collectively describe the implications of complexity science for the very foundations of management and organization studies. They are presented in three sub-sections: introductions of *key concepts*; interrogations of the meaning of complexity from different *epistemological perspectives*; and discussions of *methodological implications and tools.*

Key concepts

The chapters in this sub-section introduce important concepts from complexity science and connect them to organizational analysis.

Yasmin Merali and Peter Allen (Chapter 1) trace the evolution of *systems thinking* in the Western scientific tradition as a source of ideas about complexity and reflect on developments most likely to be influential in shaping management thinking in the future. They describe the steps that lead from earlier approaches predicated on fixed structure, fixed elements and fixed interactions to present day engagement with complexity science and the non-equilibrium dynamics of open evolving systems. Complexity science offers conceptual and methodological tools to tackle issues of emergence, self-organization, evolution and transformation by elucidating the mechanisms through which micro-level events and interactions can give rise to macro-level system structures, properties and behaviours. The chapter also shows how modelling approaches from complexity science allow us to experiment with possible worlds in which the consequences of our actions play out over time.

In Chapter 2, Raymond-Alain Thietart and Bérnard Forgues discuss the relationship between *complexity science* and *organization*. They begin with a brief survey of the contributions to organization studies made by objectivist approaches drawn from complexity science, such as theories of self-organization, deterministic chaos, path dependence and complex adaptive systems. Next, they develop propositions derived from the theories they review, and relate them to more 'traditional' organization theories. Finally, they derive some implications in the form of propositions. They counsel that future research needs to consolidate the foundations upon which complexity-science inspired organization theories are being built, through: (a) development of a consensus about disparate definitions; (b) research that draws on econometrictools to substantiate the claims of existing qualitative research; and (c) multi-level research into process dynamics.

The next contribution, Chapter 3 by Jeffrey Goldstein, addresses the phenomenon of *emergence*. He traces the origins of the construct of emergence as well as associated ideas of self-organization and dissipative structures. Six prototypes of emergent phenomena in complex systems are presented and used to identify a set of characteristics common to emergence in a wide variety of different types of complex systems, including organizations. The chapter also reviews and summarizes how the notion of emergence has been employed in organization studies. A new approach to emergence is then developed by drawing on the formalism of 'self-transcending constructions'. This concept is elaborated in a way that remedies several of the insufficiencies of the self-organization approach which currently dominates in organization studies; and offers promising paths forward for researching organizational adaptability.

In Chapter 4, Steve Maguire explores a deceptively simple question – '*what is complexity*?' – to highlight the epistemological challenges posed by complexity, which stem from issues of representation, prediction and interpretation. After a brief description of various strands of natural science from which contemporary complexity science has emerged, as well as of the features of complex systems, different definitions and measures of complexity are introduced. The chapter illustrates how both agents within and observers of a complex system are each implicated in constructing complexity. Maguire concludes by suggesting that perhaps 'complexities science' better captures the project in which scholars are engaged, since appreciating complexity involves acknowledging that competing interpretations constitute it; and recognizing that the nature of the complexity with which one wrestles derives from one's framing of and strategy for interrogating it.

In Chapter 5, Michael J. Prietula addresses important methodological issues by discussing complexity from the perspective of *computational models of organizations*. He argues that such modelling is not only viable but essential for advancing organization science in ways that bridge micro- and macro-levels of specification. He begins by describing basic properties of complex systems in the physical world; then adjusts these to reflect the social world; and presents an 'induced simplicity hypothesis' which posits that most environments in which humans find themselves call for behaviours that are simple and recurring. This perspective, with the environment viewed as a mould, provides the basis for arguing for the appropriateness and necessity of computational modelling to understand social systems. Strengthening the case for computational models even more, a series of benefits of computational modelling are also convincingly described.

Epistemological perspectives and considerations

The chapters in this sub-section explore the implications of complexity from different philosophical perspectives, as well as the implications of complexity for important philosophical questions about the nature of causality, knowledge and its limits.

In Chapter 6, Bill McKelvey advocates a *scientific realist epistemology for complexity science*, with an emphasis on 'Campbellian realism', an approach that recognizes idiosyncratic perceptions of the phenomenal world and social construction by scientific communities, but also considers 'good science' to be accountable to what is real. He begins with a critique of positivism and, in particular, positivist economics, before introducing realism, evolutionary epistemology and the 'semantic conception' of truth. He develops a 'complexity science epistemology' which is not based on ontological assumptions of reality's constituent elements being independent and combining additively but, rather, on assumptions of connected constituent elements that can interact to produce multiplicative, nonlinear outcomes. As a result, he argues, the world has four basic ontological forms, each of which is best explored and theorized with a different epistemology.

David Byrne, in Chapter 7, is also an advocate of realism, proposing '*complex realism*' as a frame of reference for evaluating the effectiveness of complex organizations such as bureaucracies formulating and implementing social policy. Byrne's approach is predicated on a quite different understanding of causality than is typically harnessed to evaluate effectiveness of these organizations – one in which causality is seen as contingent, complex and multiple. Accordingly, the techniques of 'qualitative comparative analysis' – the systematic comparison of a complex system before and after it has undergone a qualitative transformation induced, typically, as a result of a policy innovation – are appropriate to understand and manage change as well as the achievement of policy objectives. An illustration examining the performance of a subset of regional governance bodies within England's National Health System provides empirical support.

In Chapter 8, Paul Cilliers defends *poststructuralism*, which is too often incorrectly dismissed as anti-scientific and relativistic, as a philosophical stance that is inherently sensitive to the complexity of the phenomena investigated from it. Poststructuralism offers, therefore, an appropriate vantage point for interrogating the development of complexity science, a perspective which can alert complexity scholars to the seductive but dangerous attraction of traditional reductionism. Equally important, the juxtaposition of complexity science with postructuralism permits a more rigorous interpretation of the latter. An exploration of relations between complexity science and poststructuralism leads Cilliers to advocate an 'ethics of provisionality' as well as the adoption of an explicitly critical position that values transgression, irony and an aesthetically informed imagination.

Alicia Juarrero, in Chapter 9, argues that complexity science puts important questions of what constitutes *causality and explanation* on the scholarly agenda and, therefore, presents opportunities for critiquing and moving beyond dominant but impoverished understandings of these concepts within natural and social science. The revalorization of longstanding but marginalized ideas about causality, such as Aristotle's final, material, efficient and formal causes for instance, alters understandings of what can be known and controlled and, therefore, of the appropriate role of managers and organizational leaders; seen as catalysts in organic systems rather than clockmakers or controllers of mechanic ones, their objective becomes the creation of resilient organizations with the agility to self-organize in the face of changes or crises emanating from their environments.

In Chapter 10, Peter Allen and Jean Boulton explore the ontology of uncertainty, from Heraclitus through Darwin to Prigogine, in order to situate complexity science as an intellectual development that affords an understanding of *ignorance and real limits to human knowledge* as both the result of and driving force for evolutionary change. They discuss different ways of studying complex systems and illustrate how, in the mathematical modelling traditionally dominant within science, uncertainty is handled or ignored or even denied through the use of various simplifying assumptions; and explain why this is problematic. In contemporary complexity science, they see the possibility of reconciling science and history (i.e. of developing explanations that incorporate both unchanging laws and novel events) by focusing on their interplay. Modelling, they argue, still offers important advantages over other forms of knowing, but needs to be undertaken with much more humility than has been the case in the past.

Concluding this sub-section, Robert Chia (Chapter 11) explains and advocates *complex thinking*, illustrating how it has been valorized in the arts, literature, humanities and philosophy and why, therefore, these realms of human endeavour should serve as important sources of inspiration for managers seeking strategies to navigate complexity. One lesson concerns the importance of learning to recognize and appreciate what is inconspicuous, peripheral or hidden (i.e. looking at the overlooked), which often means abandoning the direct, frontal, rational approaches to phenomena so privileged in science and society. He argues that obliquity is not only legitimate but often more effective as a strategy for comprehending and engaging with complexity in social systems.

Methodological implications and tools

In this sub-section, important methodological tools from complexity science are presented and their implications for organizational analysis are discussed.

In Chapter 12, Richard Vidgen and Larry Bull discuss how computational methods inspired by *Stuart Kauffman's* NKCS *model* can better inform management and organizational research. They explore the relevance of coevolution as a phenomenon in organizational life then detail the *NKCS* model and its implementation in a particular agent-based modelling environment ('Sendero') now available online. Next, they review applications of the *NKCS* model in the management and organization studies literature. To demonstrate how the *NKCS* model can be extended and further applied to shed light on questions of importance to management scholars and practitioners, they illustrate how the model may be used to explain competitive dynamics in the microcomputer industry. They conclude by suggesting future directions for the *NKCS* model and coevolutionary research in management.

Focusing on another powerful computational method from complexity science, William M. Tracy (Chapter 13) sees at least two benefits to modelling strategic interactions of competing firms with *genetic algorithm models (GAs)*. First, unlike mathematical models, GAs allow researchers to observe the modelled systems' dynamic disequilibria, which is of particular importance because strategies employed during a period of disequilibrium affect the specific equilibrium selected by the system. Second, GAs often are better predictors of human and firm behaviour than classical game theory models. Tracy begins by explaining genetic algorithms; providing an example of a GA-based strategic model; and tracing the thinking that underpins the application of GAs to strategic analysis. After describing why GA-based model mechanisms reflect real-world decision making, he surveys existing research and outlines future directions for the application of GA-based models to strategic analysis.

Donald MacLean and Donald MacIntosh, in Chapter 14, move from simulations and computational methods to discuss the generation of insights into organizations understood as complex systems using *action research* methods. Action researchers not only study organizations but actively intervene in them with the aspiration of making a difference (i.e. of producing knowledge that allows managers to be more effective). The authors point out parallels between action research and complexity thinking; and apply the latter to the former. They then describe the use of action research to explore the application of complexity science in organizations by investigating the 'edge of chaos' in different organizational settings as well as the managerial and organizational practices that underpin it.

Concluding the *Foundations* section, Pierpaolo Andriani and Bill McKelvey (Chapter 15) explain what a power law is and why *power-law science* – the branch of complexity science addressing phenomena characterized by a high degree of heterogeneity and distributed interdependence which leads to extreme variance – is essential to management and organization studies. They argue that power-law science represents a necessary and legitimate paradigm that is more general than those currently dominating the social sciences and illustrate how it can be applied to understand entire classes of phenomena, such as extreme events and the proliferation of small niches, which are difficult or impossible to explain via Gaussian or other approaches based on finite variance.

Applications

The second section of the *Handbook* presents a series of chapters that, collectively, describe the numerous ways in which complexity science is being applied to phenomena of interest to organization theorists and management researchers. The diversity of topics addressed and approaches employed is impressive, as are the quantity and quality of insights gained. For some scholars, the challenge that complexity science represents for the Newtonian paradigm of classical science serves as philosophical inspiration for rethinking basic assumptions and tenets of traditional management thinking. For others, complexity science is a rich source of metaphors which recast organizational processes in ways that inspire novel representations and guide managerial action. For others still, complexity science represents an exciting tool kit of novel techniques and methods, including computational modelling.

In considering the applications of complexity science to organizational and management phenomena, we have divided this section into two parts. First come chapters addressing *fundamental issues of organization theory* – the relationship between an organization and its environment as well as related phenomena of organizational adaptation, change and learning. Second come chapters that address *specific management disciplines*, such as human resource management, operations, research and development, and knowledge management; or *specific management challenges*, such as leadership, entrepreneurship, the formulation of strategy to create competitive advantage and the development of corporate strategy in multiple business unit firms.

Complexity and organizing

The chapters in this section focus on organizations in their entirety and in context. They draw on complexity science to shed new light on the relationship between organizations and their environments, and to re-examine important questions about organizational adaptation, change and learning.

Max Boisot and Bill McKelvey (Chapter 16) explore the implications of complexity science for thinking about *organization-environment relations*. They revisit Ross Ashby's '*Law of Requisite Variety*' and recast it in terms of the '*Law of Requisite Complexity*', which holds that, to be efficaciously adaptive, the internal complexity of a system must match its environmental complexity. Their '*Ashby Space*', which consists of the *Ordered*, *Complex* and *Chaotic* regimes, offers a conceptual framework for thinking through the trade-offs that a system faces between stimulus simplification and response complexification as it responds and adapts to its environment. It offers scholars and practitioners a conceptual framework for thinking through some of the more pressing problems that confront a globalizing world.

Chapter 17 by James S. Baldwin situates organizations in an environment characterized by other organizations to consider the implications of complexity for *industrial ecology*. He points out that much extant research is based on reductionism and seeks to calculate optimal, equilibrium configurations. Complexity science, as well as practical considerations, suggests however that change towards a less environmentally destructive industrial ecosystem is about disequilibrium (i.e. the evolution of firms and industries). Evolutionary models that can be used to explore the probable paths of an evolving industrial ecosystem are described, and these suggest ways in which individual agents can contribute to improving the environmental performance of the overall system. Such representations can facilitate the emergence of shared interpretive frameworks and collective governance.

Glenda Eoyang (Chapter 18) surveys the academic and practice literatures to identify the various ways in which the theory and practice of *organizational change* are being altered as a result of the deployment of descriptive and explanatory metaphors drawn from complexity science. While descriptive use of complexity metaphors involves retrospective analysis of events in a change process using visual metaphors to label and categorize patterns, explanatory use of complexity metaphors assumes that the mechanisms of organizational change mimic nonlinear change mechanisms of complex systems. These latter metaphors can, therefore, provide a basis for analysis and interventions to influence change; as well as for transformation of some long-standing and unhelpful dichotomies that have shaped understandings of organizational change into more helpful 'generative paradoxes'.

John Shotter and Haridimos Tsoukas (Chapter 19) also focus on *organizational change*. They point out that the dominant epistemological orientation of Newtonian science, which privileges the general and the abstract over the particular and the concrete, contradicts common experience insomuch as novel situations are what practitioners face each and every day and, indeed, their own interventions help to generate the novelty with that they wrestle. They argue for a more ecological epistemology which is inspired by complexity science and emphasizes relations rather than entities. For human systems, in which subjectivities and communicative relations play such a fundamental role, this orientation draws attention to the constitutive role of language and conversations, which are understood dialogically to give rise to transitory but nonetheless action-guiding anticipations and the 'always unfinished openness' inherent in processes of both stability and change.

Maintaining the emphasis on how organizations change in a given environment, Eve Mitleton-Kelly and Ben Ramalingam (Chapter 20) examine the phenomenon of *organizational learning*. The chapter identifies a set of important distinctions in the literature and, in doing so, clarifies key concepts of organizational learning. The chapter then reviews and critiques research on these key concepts using the theoretical lens of complexity science, illustrating how it can be used to question, reinforce and augment extant understandings of organizational learning. Specifically, their complexity perspective provides a conceptual underpinning for the process, scope and conditions for learning; and helpfully reorients thinking about issues such as adaptation, alignment and equilibrium, the contrast between single and double loop learning, social connectedness and situated learning theories, among others.

Closing out this section on organizations in their environments, in Chapter 21 Kurt Richardson explores general implications of complexity science for the *management of organizations* by specifying what he refers to as ‘complexity thinking’. Drawing on natural science and philosophy, he argues that one implication is that complexity science confirms that there is no ‘optimal’ way to manage an organization and, consequently, the practice of management remains as much art as science. Complexity thinking implies a switch away from traditional management practices which emphasize planning and controlling to practices which emphasize learning and the evolution of managers’ knowledge *in situ* (i.e. as it is applied to concrete situations). He also derives practical lessons for managers, including that they should expect to be wrong and that flip-flopping is okay because dogmatism is rarely effective as a strategy in the long term.

Complexity and managing

The chapters in this section review how complexity science has been and can be drawn upon to theorize the management of different functional areas within an organization, and to address fundamental management challenges in novel and insightful ways.

Russ Marion and Mary Uhl-Bien (Chapter 22) present implications of complexity science for the study of *leadership*, highlighting how many contemporary organizational issues of complexity are not well handled through traditional top-down approaches to leadership. They describe three emerging complexity perspectives on leadership – adaptive leadership, administrative leadership and enabling leadership – and explore differences among them. Whereas adaptive leadership refers to informal interactions to influence local behaviours and to generate adaptive, innovative outcomes, administrative leadership refers to interactions that occur in the formal systems and structures of the organization and are designed for efficiency and control. Enabling leadership plays an important role by operating at the interface between adaptive and administrative leadership.

Human resource management is the focus of Chapter 23 by Barry Colbert and Elizabeth Kurucz, who extend Colbert’s path-breaking work which outlined how complexity science can inform the large body of strategic human resource management theory that is built upon the resource-based view of the firm. They illustrate how a particular thread of organizational complexity science – the *complex responsive processes* perspective – can be leveraged to explain how a resource-based advantage comes into being and how, in turn, an organization can build ‘competitive potential’. The advantage of the complex responsive processes perspective is in shedding light on the processes that give rise to emergent innovation and in prescribing more appropriately process-oriented roles for human resources managers.

Arash Azadegan and Kevin J. Dooley (Chapter 24) examine the *operations* function. They point out that production systems are complex adaptive systems that have been studied by operations management researchers for decades, and an important issue is that of centralized versus distributed control. Traditionally organizations have controlled manufacturing operations centrally but today it is more common for decisions about responses to changes in the organization’s environment to be taken by actors distributed throughout the system. These changes can be explained using Ashby’s law of requisite variety: the complexity of production systems has coevolved with the complexity of the environment in which they are situated. Drawing upon an historical account, they document the emergence of distributed control and link it to three factors: a plurality of organizations capable of interacting; sufficient connectivity to create opportunities to interact; and abundant resources.

Knowledge management is addressed by Max Boisot in Chapter 25. He reminds us that we act, survive and prosper via the knowledge and communication technologies we use in adapting to diverse phenomena encountered in a world which is becoming ever-more connected and complex. Complex phenomena are much higher in information content than simple ones, so managers' ability to increase and to manage their knowledge base determines how much complexity they can handle. Insights from complexity science can therefore benefit the discipline of knowledge management, as Boisot illustrates. He describes and critiques the field of knowledge management, then presents an integrative framework which is used to theorize the cyclical nature of social learning.

Knowledge is also a key theme in Chapter 26 by Pierpaolo Andriani, who explores the application of complexity science to understand *innovation*: the conversion of knowledge into socio-economic advantages via the researching and developing of new technologies. In contrast to other factors of production – land, capital and labour – knowledge is subject to virtuous cycles of positive feedback as well as network effects, which means that the more knowledge-intensive innovations a society produces, the more advantageous can become its position. So, understanding innovation is very important. Recently, there has been a shift in studies of innovation, from manufacturer-centric to network-centric approaches, and some refer to the network of interdependent, co-evolving technologies as the *Technosphere*. Complexity science provides concepts and overarching framework for making sense of the organic development and evolution of the *Technosphere*.

Continuing with the theme of innovation, Benyamin Lichtenstein (Chapter 27) reviews the application of complexity science by *entrepreneurship* scholars to research emerging ventures, explain start-up dynamics, explore the creation of new markets, trace the origins of new regional economic clusters and understand the dynamics of technology innovation. He organizes this work using a four-part typology – metamorphizing, discovering, modelling and generating complexity – to summarize how complexity science-inspired approaches have contributed to understandings of the emergence process which is at the core of entrepreneurship and to identify opportunities for future research. More boldly, he argues convincingly for a view of entrepreneurship *as* emergence, setting the stage for paradigmatic renewal in the field of entrepreneurship.

When entrepreneurs create new firms, they try to create *competitive advantage*, which is the focus of Chapter 28 by Oliver Baumann and Nicolaj Siggelkow. These authors review the literature to illustrate how complexity science, and in particular computational models of adaptation on fitness landscapes, is shedding light on the relationship between complexity and competitive advantage. Organizational complexity arises from the numerous interdependencies between intra- and extra-organizational elements, creating difficult problems of alignment or 'fit'. Is complexity detrimental to good strategy, or can it contribute to competitive advantage? Do some organization structures offer more advantage in complex environments than others? And how do a firm's strategies affect organizational performance, given internal and environmental complexity? Computational modelling has generated significant insights into these important questions.

Kathleen Eisenhardt and Henning Piezunka (Chapter 29) also address strategy, but are interested in the *corporate strategy* of organizations with multiple business units. They present and contrast traditional corporate-centric perspectives on corporate strategy with a more recent 'complexity perspective', which assumes the multiple business unit organization is a complex adaptive system consisting of modular, loosely linked and unique business units that collaborate and compete with one another. The latter perspective is business unit-centric; and focuses on processes such as 'morphing', 'rewiring' and 'patching'. It also generates quite different prescriptions as compared to traditional theories for the distribution of power and decision making in firms, the roles of actors and the management of change. The complexity perspective emphasizes the importance of a moderate degree of structure and the pursuit of coevolutionary adaptation of multiple business unit organizations with their dynamic organizational environments.

This section concludes with Chapter 30 by James K. Hazy on *management practice*. He writes for practicing executives who, he anticipates, are drawn to complexity science because traditional management research has been unsatisfactory in terms of its practical utility. He synthesizes insights from complexity science appearing in this volume to distil five new 'rules of management': (a) focus on the evolution of your organization's resilience, not design for stability; (b) be open to surprises across all levels of the organization; (c) create effectiveness by looking forwards (not backwards) and anticipating that the future will be qualitatively different from the present; (d) build models and encourage trial-and-error experimentation; and (e) recognize and reinforce larger scale patterns to ride a wave of renewal.

Be it through metaphysics, metaphors or models, it is clear from this collection of chapters that complexity science is transforming understandings of organizing and of managing.

Interfaces

With its trans-disciplinary roots and appeal, a complexity perspective also opens up promising avenues of interface between organization studies and other disciplines. Accordingly, the third and final section of the *Handbook* introduces a series of interfaces where exciting research is occurring, facilitated by a couple of factors. First, complexity science is in the process of transforming conventional thinking in a number of fields beyond management, and the changes underway present opportunities for challenging traditional paradigms, for doing science differently, and for initiating new conversations. Second, the common language and set of concepts provided by complexity science can facilitate conversations across disciplinary boundaries. Creative destruction is taking place and the boundaries between management and adjacent disciplines represent sites for innovative theorizing. This section therefore highlights how complexity science is being applied in several non-management fields and, in so doing, creating exciting interfaces for constructing knowledge that bridges management to other disciplines.

In the first chapter in this section (Chapter 31), Stephen Guastello looks at the application of complexity science, and in particular research on nonlinear dynamics, to theoretical and practical problems encountered in *psychology* that are also relevant to management. The chapter first considers applications in cognitive science, in which consciousness is viewed as an integrated process which brings together psychophysics and sensation processes, perception, cognition, learning, memory and action. Here, the emphasis is on an individual in a complex environment. Next, it considers collections of individuals, reviewing insights gained into social cognition, motivation, conflict, creative problem solving, group coordination and leadership emergence. The direct relevance of these phenomena to management is clear, and complexity science therefore presents opportunities for strengthening ties between the disciplines of psychology and management.

Next, César Hidalgo (Chapter 32) looks at how *network sociology* can contribute to understanding complexity and management. He proposes that, because organizations can be seen as adapting, evolving networks of interacting entities (i.e. as complex systems), many insights from network theory apply. He also highlights how value often originates 'in between' (i.e. in the relationship that connects) multiple entities, which means that network theory can also inform management theories of value creation and destruction.

Network science – sensing methods and analytical techniques combined – can assist organizations to become more self-aware, which will increase their likelihood of successfully adapting to their environment. Further, more adaptable organizations could, collectively, contribute to an overall economic or societal system that itself is more evolvable.

In Chapter 33, Steven Bankes examines the use of complexity science in *public administration and policy*. He observes that policy decisions, whether made by government agencies, for-profit companies or individuals, typically concern systems that are both complex and open. As a result they give rise to 'wicked problems': not only must policy be adaptive to cope with deep uncertainty and changing circumstance, but its analytic structures are also context dependent, requiring adaptive responses because policy coevolves with the system towards which it is directed. Bankes focuses on the use of computational models to support exploration of alternatives in policy making, considering both possible advantages and potential dangers. Methods for parametric v. non-parametric exploration are discussed, as are analyses of policy alternatives, uncertainties, values and sources of information, as well as the role of iteration and interactivity.

The next chapter, by Geoffrey Hodgson (Chapter 34) adopts key assumptions of *evolutionary and institutional economics* to explore habits and routines – both of much interest to organizational researchers – as adaptive responses to complex environments. He shows that the Darwinian approach provides an overarching framework for theoretical and empirical exploration of the mechanisms involved in learning, knowledge transfer, competition and organizational change. He notes that discussions of the complexity facing agents and the mechanisms required to deal with it are less prominent in the literature on complexity, but of critical importance to understanding social evolution. In the approach outlined in the chapter, individual habits and organizational routines are viewed as different replicators and as part of the multi-level evolutionary process which characterizes a society.

Chapter 35 by Paul Ormerod looks at the application of complexity science to *economics*, which is creating a rich interface for research into complexity, management and economics. He notes that there are several key features of complex systems that suggest that the perspective of complexity science offers perhaps the best vantage point for analysis of an economy. He begins by considering the behaviour of economic actors and whether the assumption of economic rationality can be justified, underlining just how problematic such assumptions are. Experimental and behavioural economists, however, have documented how actors use limited information and rules of thumb, each one customised to particular circumstances. Consistent with these approaches, he examines firm behaviour from a complex systems perspective, including an illustrative example using agent-based modelling.

The section concludes with Chapter 36 in which Brenda Zimmerman reviews and organizes the literature on *health care*, explaining how complexity science has been tapped for insights to address public policy, clinical and management challenges. For policy makers, complexity science provides inspiration for redesigning health care delivery systems; for clinicians, applications of complexity science range from relationship-centred care to the use of fractal geometry for diagnosis and treatment of cardiac conditions; while for health care managers and leaders of health care organizations, the application of complexity science has resulted in the redesign of work roles as well as change in care delivery modes and patient safety initiatives. Complexity science applications to health care have been transformative insomuch as they have been harnessed to design and justify more distributed network-based models of control and authority.

Complexity science is not only transforming our understanding of organizing and managing, it is transforming thinking about a range of phenomena in disciplines beyond management. Scholars should therefore take advantage of the opportunity they have to participate in the creative destruction of traditional ways of thinking and of artificial boundaries separating our academic discipline from others.

COMPLEXITY AND MANAGEMENT: LOOKING TO THE FUTURE

As the contents of this *Handbook* show, a diverse set of researchers adopting a wide range of approaches and studying an impressive variety of organizational phenomena are coming together to constitute the field emerging at the intersection of complexity science and management. Complexity science confirms that our world is not one resembling a machine set in motion at the beginning of time and changing deterministically in an event-free manner since. Rather, it more resembles an ecosystem or organism in the process of developing, dissipating the sun's energy in ways that give rise to events at different scales and, hence, unpredictable qualitative change. This is not to say that there are not times and places where assumptions of an unchanging underlying ontology will yield satisfactory theories and models; but it is to say that the search for universal laws governing relations among things is largely misguided. Similarly, approaches to phenomena which assume equilibria need to be questioned. These realizations, of course, have important implications for the practice and study of management.

Organizations make up and operate in a Schumpeterian world of creative destruction – an under-determined social and economic reality which is not at, nor heading for, 'equilibrium' and in which behaviours cannot be interpreted as being 'optimal'. Rather, our societies and political economies are complex systems in which numerous elements interact. Humans and their organizations are guided by imperfect schemata that are revised as a consequence of experiences, leading to changed behaviours and innovations. This, in turn, gives rise to novel situations for actors at the next moment in time, meaning new experiences and more changes to schemata, and so on: the learning process continues but a given schema does not necessarily converge towards some accurate representation of reality because the latter is not fixed and is always 'becoming'. If selection pressures operate at the level of agents in addition to schemata, eliminating non-viable or unlucky ones while others survive, then evolution complements learning. But, contrary to the view of markets from neoclassical economics, the mere presence of a firm does not imply that its performance or profits are optimal. Rather, it implies that its performance has been sufficient to allow it to participate in the ongoing drama of creative destruction for at least a little while longer. Accordingly, the practice and study of management is redirected away from traditional approaches which emphasize centralized calculation of optimal actions to navigate a knowable environment and implemented through command and control, to alternative approaches which emphasize actions as experiments (i.e. explicitly recognized opportunities for learning, which flow from distributed judgments and yield knowledge which is contingent and provisional). In a complex world, hubris can lead to disaster, while the payoffs to such qualities as humility, doubt and mindfulness towards assumptions and beliefs which might otherwise become taken for granted are much larger than one might expect.

Philosophical issues of ontology and epistemology therefore loom large in this shift and, notably, for *both* practitioners and researchers. As several chapters in this *Handbook* argue and illustrate, complex systems change qualitatively as new global features and new types of entities emerge over time, giving rise to an evolving, changing ontology. In other words, the very entities that we use as the basis for our descriptions and theories themselves can change over time. This is the case for managers employing theories in action and for organizational scholars developing theories from observations. For the former, a premium is placed on attending to their organization's capacities for adaptation and learning; this necessarily implies a need for more explicit attention to the 'organizational epistemology' (von Krogh and Roos, 1995; Tsoukas, 2005) that their organization is enacting (i.e. how knowledge is produced and used *in* and *by* the organization). For the latter, scholars suggest embracing a new 'normal', 'quasi-natural' and model-centred (McKelvey, 1997; McKelvey, this volume) 'bottom up' science (Epstein and Axtell, 1996) for producing and using knowledge *about* organizations. Related, to fully embrace complexity both management practitioners and organizational scholars need humility as regards what they think they know about organizations since complexity science points to unavoidable limits to knowledge (Allen, 2000, 2001, this volume), as well as appreciation of the multiple divergent yet legitimate descriptions which are constitutive of complexity (Cilliers, 1998; Maguire, this volume).

What, then, are the implications of complexity science for future management and organizational research? What are the most pressing next steps in advancing management research on this front? Each of the chapters which follow provides at least partial answers to these questions and it would be difficult, if not downright foolish, for us to try to synthesize them here given the breadth of topics covered and heterogeneity of perspectives represented. The diversity of *applications* of complexity science to organizational questions and sheer number of *interfaces* to other disciplines potentially bridged by complex adaptive systems approaches present us with a daunting task. Simply – and perhaps appropriately for a subject matter such as 'complexity' – the field emerging at the intersection of complexity science and management does not lend itself to a single research agenda. It is unlikely that a research programme addressing such a wide range of phenomena – from leadership to human resource management to innovation to organizational learning to operations management to organizational change through talk, to name just a few of the topics covered by the chapters of the *Handbook* – could be coherent. As a result, we focus on the *foundations* of knowledge in and about organizations, drawing attention to the old but persistent issue of 'uncertainty' as well as to new and promising computational methods.

Unpacking Uncertainty with Complexity

Uncertainty is a 'central concept in the organization theory literature, particularly in theories which seek to explain the relationship between organizations and their environments' (Millikan, 1987: 133). Indeed, Thompson (1967: 159) argues that '[u]ncertainty appears as the fundamental problem for complex organizations, and coping with uncertainty, as the essence of the administrative process'. Similarly, Davis and Powell (1992: 317), in describing the development of theory on organization-environment relations, note that '[u]ncertainty is one of the most critical features of the environment', with contingency theory, resource dependency theory and transaction cost economics each positing that 'a good deal of organizational behaviour consists of adaptive responses to environmental uncertainty', and emphasizing exchange relations 'as the primary source of uncertainty'. If uncertainty is so central to organizing, what does an understanding of complexity science imply for organizational research?

First, if organizations and their environments are complex systems, then uncertainty is unlikely to be completely reduced due to 'nonlinearity, which means that small causes are associated with disproportionately large effects in a system's state variables' and that a complex system's evolution displays 'sensitivity to initial conditions, sometimes referred to as the "butterfly effect" after meteorologist Lorenz's (1972) claim that the flap of a butterfly's wings in one region of the world could affect weather patterns in others' (Maguire et al., 2006: 166). Another reason why uncertainty is likely to be a permanent and problematic feature of complex organizations and complex organizational environments is that there are limits to knowledge in and about complex systems (Allen, 2000, 2001, this volume). Knowledge of the future, in the form of accurate predictions, is limited because *the* future does not exist in the present awaiting discovery through human cleverness or the raw application of computational power. Rather, multiple possible futures exist. Further, the present can be as problematic as the future because one feature of complexity is that it is constituted through multiple competing yet legitimate descriptions, giving rise to yet more uncertainty, although of a different kind.

Accordingly, we believe the time is ripe to unpack and explore the concept of uncertainty and its relation to complexity. Important questions that scholars could explore are: What is the nature of the uncertainty/uncertainties to which organizations attend? To which internal and external sources of uncertainty do (or should) organizations attend? How are (or should) resources be allocated to avoiding, reducing or eliminating the various forms of uncertainty from different internal and external sources? How does the uncertainty faced by an agent in a complex system evolve over time? How do patterns of uncertainty facing multiple agents evolve over time in a complex system? What is the relationship between uncertainty, risk and complexity?

Let us elaborate on the first question, for which some guidance comes from scholars wrestling with the issue of uncertainty in contexts where what is at stake in decision making is not generating adequate return on investment or the survival of a given organization but, rather, the survival of our planet and the peoples on it. Debates around climate change, nuclear energy, toxic substances and genetically modified organisms, to name but a few, often hinge on scientific uncertainty in and about complex systems and how to proceed in the face of it. As a consequence, sophisticated epistemological and ethical critiques have developed around the notions of risk and uncertainty, the distinction between type I and type II errors, and the inevitability of value judgments even within the soundest of science. For example, a bias for minimizing type I errors at the expense of more type II errors (e.g. the ubiquitous use of 95% confidence intervals and 5% significance levels in hypothesis testing) may make sense in *pure* science where the consequences of false negatives is merely the inconvenience of a false belief in the laboratory; but when it comes to *applied* science decisions for which the consequences of false negatives are serious and irreversible harms (e.g. issues of technology or ecology) the situation is quite different; see for example McGarvey (2007) on the consequences of false negatives to the question of whether a species is endangered. Stirling (1999), to give just one illustration, distinguishes four types of 'incertitude' using the dimensions of 'knowledge about outcomes' and 'knowledge about probabilities', each of which can be 'problematic' or not: *risk* exists when neither knowledge about outcomes nor about probabilities is problematic; *uncertainty* is present when only knowledge about probabilities is problematic; *ambiguity* exists when only knowledge about outcomes is problematic; and *ignorance* is the label for situations when both knowledge about outcomes and about probabilities is problematic.

Given the tendency towards loose and imprecise use of the term 'uncertainty' in much management research, organization theory could benefit from a more nuanced and systematic approach. Using Stirling's (1999) typology, the qualitative changes inevitable in an evolving complex system mean that managers face much more ambiguity and ignorance than one might guess if one looked only at the management literature where the concepts of risk and uncertainty predominate. In sum, exploration of the relationships among uncertainty, risk and complexity is likely to prove fruitful.

Modeling and Narrating Complexity

The underlying heterogeneity of the entities which make up organizations and their environments, as well as the empirical reality of qualitatively novel features emerging in them over time as they move through successive states of disequilibrium, pose epistemological and methodological challenges for organizational researchers. Fortunately, complexity science offers methods for addressing those management phenomena that involve order creation along with changing ontology, as opposed to unchanging entities subjected to forces pulling them inevitably toward some equilibrium. As Maguire et al. (2006: 197) write:

> Further, the shift from elegant mathematical representations of idealized processes to agent-based computational models also allows organizational researchers to pursue the epistemological advantages of models and experiments without having to assume away important – or, as some would say, essential – features of organizational reality simply to make the mathematics tractable. These include idiosyncratic heterogeneity among individuals or firms, commonly eliminated by assuming homogeneity; interdependence among agents, commonly eliminated by assuming independence; and the emergent outcomes of agent interactions, commonly ignored because equations necessarily focus on relations among variables at a single level of analysis, treating fast variables as insignificant noise and slow variables as unchanging constants. … So, instead of conceptualizing and studying the world as made up of independent homogeneous agents responding as automatons to equilibrating forces – seemingly without choice or, equivalently, with omnisciently rational choice – bottom-up science offers a more realistic alternative.

As numerous chapters in the *Handbook* illustrate, computational modelling and the use of 'agent-based models' (ABMs) in organizational research is contributing much to our understanding of management. Complexity science represents an important development for organizational scholars (and economists) because it provides theories appropriate to Schumpeterian competition and offers mathematical and computational tools to study creative destruction in economic sectors as a complex evolutionary system. Instead of modelling each agent according to a single profit- or utility-maximizing algorithm, researchers can explore much more heterogeneous situations where different behavioural rules interact and responses play out over time, leading to a much more realistic view of markets. To understand the dynamics of a changing world that is constantly in flux, insights that stem from assumptions of perfect knowledge (which may then be subsequently relaxed) in order to generate mathematical puzzles that are solvable can be complemented with insights from computational models that start from assumptions of agents having no knowledge but acquiring it over time through experience. Indeed, the latter may be superior to unravel the mysteries of emergent features, characteristics and capabilities that lead to increasing levels of coordination, hierarchical structures and system-level organization.

In addition, for managers and policy makers who wish to manage a given system and who are deliberating the merits of a given strategy or policy intervention, absence of knowledge about the ways in which different elements of the system may interact as they respond to the intervention represents a real empirical problem. However, computational models can be used to capture aspects of the system that are relevant to the decision maker while representing the system in terms of the interacting agents that inhabit it. In this way, the evolution of the system can be examined under the influence of different policies and actions and can be run repeatedly with different random elements to explore the stability of any particular type of trajectory and the sensitivity of outcomes to changes in parameters. Such models can not only help to shed light on different possible futures but can also reveal collective outcomes that were not anticipated by the manager or policy maker.

Thus, the harnessing of computational modelling techniques originating in the study of complex systems by organizational scholars is yielding many insights. These contributions can be juxtaposed with numerous other chapters in the *Handbook*, which illustrate how concepts and ideas from complexity science have also contributed to the qualitative methods used to explore organizational phenomena. Perhaps it is too early in the development of the field to expect more integration, but we propose that future research should be more attentive to synthesizing computational modelling of emergence and narratives of emergence from qualitative research, reiterating a point made not long ago by Maguire et al. (2006: 201):

> Ideally, agent-based models (ABMs) would bring experimental corroboration and elaboration to findings from narrative studies. ABMs could offer tests for broadening generality and for studying dynamics. ABMs also allow the juxtaposition of variables from different disciplines. Thus, narrative studies could be more multidisciplinary. Narrative researchers can also help to develop better ABMs by offering clearer data for the purpose of validating baseline models. Thus, ABMs would simulate the narrative findings first, and then advance into experimental manipulations. Qualitative researchers should also design studies to enlighten or challenge model-centred findings.

This appeal for integration of computational and qualitative methods is consistent with recent claims of scholars that 'an appropriate aspiration for organization theory in the early twenty-first century is providing a natural history of the changing institutions of contemporary capitalism' by studying 'mechanisms' (Davis and Marquis, 2005: 333): computational models can be used to elucidate mechanisms at work when particular patterns arise; while narratives developed from qualitative methods can identify the specific individuals, organizations and events that, in retrospect, turn out to have been determinant in the natural history of a given economic sector's 'becoming'.

FINAL WORDS

As the chapters in this *Handbook* demonstrate, complexity science offers a range of novel conceptualizations and approaches for understanding the processes that govern and drive the emergence, development and demise of a range of interacting entities (e.g. people, business units, organizations and societies) as they cooperate and compete in open systems, drawing resources from each other and their environments. Almost mathematical in its level of abstraction and metaphysical in its implications, complexity science provides firm *foundations* for organization studies, with robust philosophical underpinnings, concepts and methods; innovative *applications* which shed light on important organizational phenomena; and promising *interfaces* for launching fruitful conversations between organizational and other types of scholars. With so much to recommend in the chapters that follow, perhaps the best way to conclude this introduction is simply to encourage you to discover each of them individually and to wish you many pleasant hours of what we are convinced will be stimulating and enjoyable reading.

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PART I

Foundations

A

Key Concepts

1

Complexity and Systems Thinking

Yasmin Merali and Peter Allen

> Once the whole is divided, the parts need names.
> There are already enough names.
> One must know when to stop.
> Knowing when to stop averts trouble.
> Tao in the world is like a river flowing home to the sea.
>
> Lau Tsu, Tao Te Ching

INTRODUCTION

Systems thinking has evolved over the millennia as people have looked for ways to articulate the features of the world around them in a coherent manner.[1] Starting from the definition of a system as an integrated whole made up of interconnected parts, various formalizations of systems thinking in a way that would be of interest to managers have emerged over time as people have looked for ways of rationalizing their interactions with the world. These formalizations give us a set of ontological and epistemological devices that have been used to define what the world is, to explain how it works, and to define and justify interventions that are intended to change, control or constrain the future behaviour of that world.

The ancients debated the role of structure, form and composition[2] in determining the behaviour of social, physical and natural systems, and engaged with the transience of system phenomenology,[3] and we find these themes recurring in modern theories of systems behaviour. Successive schools of systems thinking have focused on specific aspects of systems properties, and developed an apparatus to confront the challenges of their time in dealing with complexity.

In this chapter we track the evolution in the Western scientific tradition of systems ideas to deal with complexity, and reflect on the developments that are most likely to be influential in shaping management thinking from here on.

Our account takes us from Bertalanffy's biologically inspired GST (General Systems Theory), through the cybernetics of the Macy Group and the analytical ethos of systems engineering, the theories of self-organization and self-production in chemistry and life, to the present day engagement with the ideas of complexity science.

This trajectory crosses and re-crosses traditional divisions between the physical, biological and chemical sciences, and it takes us from the Newtonian predictability of the trajectories of complex dynamical systems in space to the present day challenges of dealing with the unpredictable trajectories of complex dynamical systems in space-time. We shall see how the different conceptualizations of systems and their complexity have affected the ontological and epistemological assumptions for successive models for managing complexity in socio-economic contexts.

SYSTEMS THINKING

Based on the definition of a system as an integrated whole made up of interconnected parts, axiomatic to traditional systems thinking are:

- the existence of a distinct entity that can be identified and explicitly defined as 'the system' or 'the whole';
- the composition of 'the whole' from a number of *inter-connected* parts; and
- the existence of distinctive properties that can be ascribed to 'the whole' but not to any of the individual parts that constitute 'the whole' (i.e. 'the whole' is more than the sum of its parts).

Systems thinking is often defined by its contrast to the Cartesian paradigm which is characterized by the belief that the behaviour of the whole can be understood entirely from the properties of its parts. Systems thinking, on the other hand, asserts that systems cannot be understood by analysis – the properties of the parts can only be understood within the larger context of the whole.

The composition (what the components are (made of)), structure (how the components are connected) and organization (how the components interact to maintain the coherent existence of the system as a distinctive 'whole') of a system together define the identity of the system at any given moment. As we shall see, these three aspects have received varying degrees of attention in the different families of systems thinking and practice that have evolved in diverse fields and been adopted and adapted by management thinkers to deal with complexity over the years.

General Systems Theory

The formalization of modern day systems thinking goes back to Ludwig von Bertalanffy's formulation of the General Systems Theory (GST) in the first half of the twentieth century as

> … an important means of controlling and instigating the transfer of principles from one field to another, and it will no longer be necessary to duplicate or triplicate the discovery of the same principle in different fields isolated from each other. (Bertalanffy, 1968)

In his exposition of the GST in 1940, Bertalanffy argued that the laws of classical physics that could be applied to predict the behaviour of physical systems were based on assumptions of systems closure and equilibrium dynamics that did not hold for biological systems. So, for example, whilst the Second Law of Thermodynamics states that the entropy (associated with the degree of disorder) of an isolated (closed) system which is not in equilibrium will tend to increase over time, approaching a maximum value at equilibrium, living systems are open systems capable of maintaining ordered steady states under non-equilibrium conditions. This sets the stage for subsequent developments in systems thinking directed at understanding the dynamics that underpin the maintenance of order in open systems. Bertalanffy provided a point of connection for other developments in the study of open systems in diverse fields.

In the management field, systems thinking began to erode the Newtonian paradigm of a clockwork universe governed by deterministic laws of nature. Developments in the earlier part of the twentieth century were predicated on the design paradigm for management and problem solving. The emphasis was predominantly on the design of organizations as systems that could be regulated and controlled by management intervention. Later developments signalled a shift away from the design paradigm, as organizational scholars began to engage with ideas of self-organization, emergence, adaptation and co-evolution as mechanisms to explain the unintended consequences of designed management interventions.

The science of cybernetics, Maturana and Varela's conceptualization of autopoiesis (Maturana and Varela, 1973) and Prigogine's work with dissipative systems (Prigogine, 1967) are amongst the most influential forces in the evolution of ideas about the management and organization of systems. Cybernetics focused on mechanisms for control and co-ordination in machines and organisms, and gave rise to management theories for organizational design in the first part of the twentieth century. Maturana and Varela focused on the patterns of process and organization that defined living systems, and their work has been influential in the development of theories of self-organization and the maintenance of identity in social systems (Luhmann, 1990; Merali, 2002). Prigogine's work was influential in the development of ideas about the dynamics underpinning organizational transformation – shifting the focus from being to becoming.

THE DESIGN PARADIGM

In this section we look at the contributions of cybernetics and systems engineering to management thinking. Both approaches grew out of the research activity in the Second World War, and were influential in the development of management ideas about the way in which organizational structure and control mechanisms could be designed in order to meet the challenges of managing large, complex systems.

Whilst systems engineering focused on controlling complexity by breaking down large organizational structures into smaller, more manageable ones, cybernetics raised the attention of managers to the organizing *principles* that governed the nonlinear dynamics of structurally stable systems.

Cybernetics: patterns of control

The cybernetics movement began during the Second World War. Norbert Weiner coined the term cybernetics from the *kybernetes* (steersman) and defined it as a new science of 'control and communication in animal and machine'. The conceptual framework for cybernetics was developed in the Macy meetings (the first of which was held in 1946). The multidisciplinary membership of the Macy group included Weiner, von Neumann, McCullough, Shannon Mead and Bateson. Their agenda of developing a self-guiding, self-regulating machine ran alongside an interest in discovering the common principles of organization in diverse systems and in understanding the neural mechanisms underlying mental phenomena to create an exact science of the mind. Subjects like complexity, self-organization, connectionism and adaptive systems had been initiated already in the 1940s and 1950s.

The participants of the Macy conferences went on to make a number of important contributions to the fields of computer science, artificial intelligence, cognition, philosophy, information theory, economics, and ecology. John von Neumann's invention of cellular automata and self-reproducing systems has been incorporated into modern-day complexity science modelling approaches.

A major contribution of cybernetic movement to management science in the early part of the twentieth century was the conceptualization of feedback loops between system components as regulating mechanisms for the system's performance. The overall regulatory mechanism for the system is based on the existence of a circular arrangement of causally connected components – the output of each component either has a positive or negative effect on the output of the next component. The overall behaviour of the system depends on the cumulative effect of all the links between its components – a system containing an odd number of negative links will display a self-balancing behaviour, whilst one that has an even number of negative links will display a self-reinforcing exponential runaway behaviour.

The fundamental contribution of this conceptualization to general systems theory was the distinction of the *pattern of organization* from physical structure.

The early developments in management science based on cybernetic principles focused on the exploitation of negative feedback loops for the self-regulation of systems and the maintenance of stability. The importance of positive feedback mechanisms only entered mainstream management thinking in the 1990s along with the interest in understanding the network dynamics underpinning discontinuities in the competitive landscape.

Two of the most prominent developments derived directly from the cybernetic movement in the field of management are Jay Forrester's System Dynamics and Stafford Beer's Viable Systems Model.

System Dynamics

System Dynamics grew out of Forrester's work on applying the theoretical apparatus of control theory and the nonlinear dynamics associated with the feedback mechanisms of cybernetics to 'enterprise design' in the 1950s.

It is predicated on the development of models that define an enterprise in terms of the structure of the feedback loops underpinning its dynamic behaviour. The focus of the model is on the long-term patterns and internal organizing structure of closed information loops and their role in controlling and regulating the enterprise's behaviour in response to exogenous stimuli and endogenous fluctuations.

Over the years there has been a proliferation of modelling tools for System Dynamics to enable the representation of the causal structures of problems in terms of stocks and flows and feedback loops. The overall pattern of the feedback relationships is defined. The use of such tools has been important in promoting the use of System Dynamics models to design policy interventions and to test the potential of these interventions to effect desirable outcomes by affecting the relative potency of feedback loops. In particular, by supporting the modelling and simulation of complex systems with large numbers of variables within multiple interacting feedback loops, System Dynamics enables decision makers to explore the potential of their interventions to generate unintended consequences. In practice, the predictive power of System Dynamics simulations and their utility for designing interventions is limited by the extent to which a persistent set of feedback mechanisms and their causal effect can be defined for the lifetime of the model.

In systems where it is possible to accurately identify the pattern of feedback loops and the assumption of structural stability holds – i.e. new variables and equations do not appear during the time that the 'simulation' represents, System Dynamics models can be useful, and their predictions meaningful. However, this is no longer the case if the assumption of structural stability ceases to hold – e.g. if new mechanisms and innovations appear, or resources and factors that were not even included in the original model suddenly become important, or people change their behaviour. So, a System Dynamics model may be useful within the time span that its structure actually agrees with that of reality, but could be very misleading if this strong limitation was neither stated nor understood.

The Viable System Model

The Viable System Model (VSM) also originated in the 1950s, and was conceived by Stafford Beer as a generic blue-print, or template, for the organizing structure of any autonomous system. According to Beer, any organization can be defined in VSM terms as a set of systems nested within systems, embodying a recursive organizing structure.

The generic VSM template comprises a configuration of what Beer defines as the:

> … five necessary and sufficient subsystems interactively involved in any organism or organization that is capable of maintaining its identity

> independently of other such organisms within a shared environment. (Beer, 1985)

The generic VSM template is replicated at all levels of detail within the nested structure: the organizing architecture is fractal in nature, displaying the self-similar VSM template at every level.

Labelled as 'Systems 1–5' the subsystems respectively take care of the primary function of the organization, information and communication, governance, environmental monitoring, policy and strategy. According to the VSM theory, an organization is viable if and only if it has this specified inter-related set of management functions embodied recursively at all levels of organization. If any of the subsystems are absent or defective, the viability of the organization will be compromised.

VSM has been widely used for organizational diagnosis and design: its fractal nature unifies its application at all scales to define the management structures for maintaining a cohesive organizational structure and identity. Beer's own work on the diagnosis of socio-political systems illustrates the grand scope of VSM applications.

System Dynamics and VSM conform to a *design* worldview based on assumptions of structural stability, such that desired behaviours of complex systems can be brought about in a largely deterministic manner by management interventions on feedback loops. This view has sometimes been criticized for 'reifying' some temporary description, and for not taking into account the non-rational behaviour of human actors and the emergent aspects of collective behaviours. This criticism has been even more strongly levelled at the other strand of systems thinking (Systems Engineering) that grew out of the research activity from the Second World War.

The engineering of systems: constructing complex structures

In addition to the emergence of the cybernetic movement, a more analytic approach to dealing with complexity also grew out of the operations research activity in the Second World War, based on the definition of systems in terms of hierarchical structures and modular organization. At any level in the hierarchy the system could be partitioned into a set of interacting subsystems, which could themselves be decomposed further into subsystems at successively more granular levels of detail. The technical and management challenge lay in the partitioning of projects, systems and development work without losing the holistic view of the system. The conceptual challenge lay in the definition of boundaries and interfaces in a way that would preserve the integrity of the reassembled whole. This strand of systems thinking, typified by Systems Engineering and Software Engineering (often classified as the 'hard' systems approaches) focused on the internal consistency of modularized systems, whilst Soft Systems Methodology focused on the problematic definition of the 'whole' for human activity systems.

Systems Engineering

Systems Engineering as an approach and methodology grew in response to the increased size and complexity of systems and projects, it:

> recognizes each system is an integrated whole even though composed of diverse, specialized structures and sub-functions. It further recognizes that any system has a number of objectives and that the balance between them may differ widely from system to system. The methods seek to optimize the overall system functions according to the weighted objectives and to achieve maximum compatibility of its parts. (Chestnut, 1965)

This engineering approach to the management of complexity by modularization was re-deployed in the software engineering discipline in the 1960s and 1970s with a proliferation of structured methodologies that enabled the analysis, design and development of information systems by using techniques for modularized description, design and development of system components. Yourden and DeMarco's Structured Analysis and Design, *SSADM*, James Martin's Information Engineering, and Jackson's Structured Design and Programming are examples from this era. They all exploited modularization to enable the parallel development of data, process, functionality and performance components of large software systems. The development of object orientation in the 1990s exploited modularization to develop reusable software. The idea was to develop modules that could be mixed and matched like Lego bricks to deliver to a variety of whole system specifications. The modularization and reusability principles have stood the test of time and are at the heart of modern software development.

Introducing the axiological dimension: soft systems thinking

Whilst the cybernetic approaches had their roots in the desire to construct a self-guiding, self-regulating machine and create a science of the mind, and both VSM and System Dynamics have been used to explore aspects of social systems, none of the approaches covered so far dealt explicitly with human values and motivation.

Peter Checkland's conceptualization of the Soft Systems Methodology (Checkland and Scholes, 1990) grew out of his critique of the way in which systems engineering methods neglected the human dimension of the context within which systems were conceived and used. Soft Systems Methodology (SSM) is important in the history of systems engineering because of its explicit treatment of human purpose and value-based perceptions. Whilst the systems engineering approaches focus on the efficacy and internal consistency of systems specifications and their development – i.e. building the system right, SSM focuses on the often contested question of what the 'right' system should be. Subsequent attempts have been made to fuse SSM with the structured approaches of systems engineering, but SSM remains at its most powerful when used freely as an approach for exploring, making sense of, and defining multiple views of problem situations and their potential solutions.

SSM can be used both for general problem solving and in the management of change. Its primary use is in the analysis of complex situations where there are divergent views about the definition of the problem situation (e.g. How to improve health services delivery; How to manage disaster planning; When should mentally disordered offenders be diverted from custody? What to do about homelessness amongst young people?), and the transformation that it needs to undergo.

In SSM the problem situation is viewed as a human activity system with multiple stakeholders having different perceptions about the system and its purpose. In the early stages of the method each stakeholder is engaged in defining explicitly what the problem situation is, and what transformation it must undergo to achieve a more desirable state of affairs. As part of this exercise each stakeholder has to make explicit the *Weltanschaaung* (the 'world outlook' and value assumptions) that the transformation definition is based on. Each stakeholder then goes on to define the activities that must be undertaken to deliver the transformation, along with the requisite resource requirements and criteria for evaluating the effectiveness, efficacy and efficiency of the proposed transformation. The different stakeholder 'models' of transformation are then fed into a collective debate and discussion with the objective of arriving at a decision about the way forward that would be systemically desirable and culturally feasible.

Whilst SSM (along with other approaches arising out of the more general socio-technical school of management and critical systems thinking) was important in pointing to the importance of human and social values and perceptions in decision making and its outcomes, it remains within the design paradigm. Its focus is on specifying and designing the 'right' system intervention to achieve a desired state of affairs. Whilst it highlights the messiness of human activity systems and acknowledges the diversity that is accommodated in social organization, its design is to enable all stakeholders to see the whole, diverse problem space, and to take a collective decision about the best way forward.

Models in the design paradigm

Making models of complex systems and situations is a powerful way of understanding and testing the assumptions that we make about the structure and dynamics of systems.

We understand situations by making creative, but simplifying assumptions. We define the domain in question (the boundary) and by establishing some rules of classification (a dictionary) that allow us to say what things were present and when. This means that we describe things strategically in terms of words that stand for classes of objects. The value associated with an element in a model (e.g. number, price) may be both related to the internal state of the element and also affected by processes or mechanisms that link it to other elements. This allows us to understand the changes in a variable in terms of both internal conditions and also the changes that occur in the values of the other variables within the system. If the purpose of defining the system is to achieve an explanation of the linked changes in the values of the different components, then we need to include within the system the majority of causal links possible, and allow weaker links to be left in the environment. In other words, there may be a succession of levels of description corresponding to the natural clustering of linkages, such as for example, atoms, cells, organisms, groups, firms, industries, economies, societies up to the planet. The point is that in using a systems approach to characterize a situation, there are really three levels of description involved: the internal nature of the elements; the different variables in interaction making up the 'system'; the effects and links connected to the system environment.

The staging posts in the evolution of systems thinking have all been associated with different types of assumptions about what constitutes a 'good enough' abstraction of reality as a basis for the development of models that would allow us to:

- make predictions about future system states; and
- define interventions in the present that would generate desired behaviours of the system at some future point.

In Figure 1.1 we show how successive assumptions are made in the development of models in order to 'understand' the real situation. On the left-hand side we have the 'cloud' of reality and practice. Approaches like SSM engage with this by attempting to capture and systematize descriptions of perceptions of reality from different stakeholder perspectives.

The 'science' of modelling begins by deciding on a boundary within which an explanation will be attempted, in the context of the environment outside. The second assumption is that of classification. The elements present within the boundary are classified into types, so that potentially, previously established behaviour and responses of similar types can be used to predict behaviour. In examining any evolving system of interest over some long time, however, it will be found that qualitative evolution has occurred in which some types of component have disappeared, others have changed and transformed, and others still have appeared in the system initially as innovations and novelties.

Figure 1.1 shows us how starting from 'reality' on the left, about which no assumptions have been made, different types of representation and model can be made providing that the necessary assumptions hold (Allen et al., 2007). These different representations pass from one of pure acceptance through various intermediate views to one of complete deterministic certainty when prediction is believed possible. In the development of these representations and understandings of a

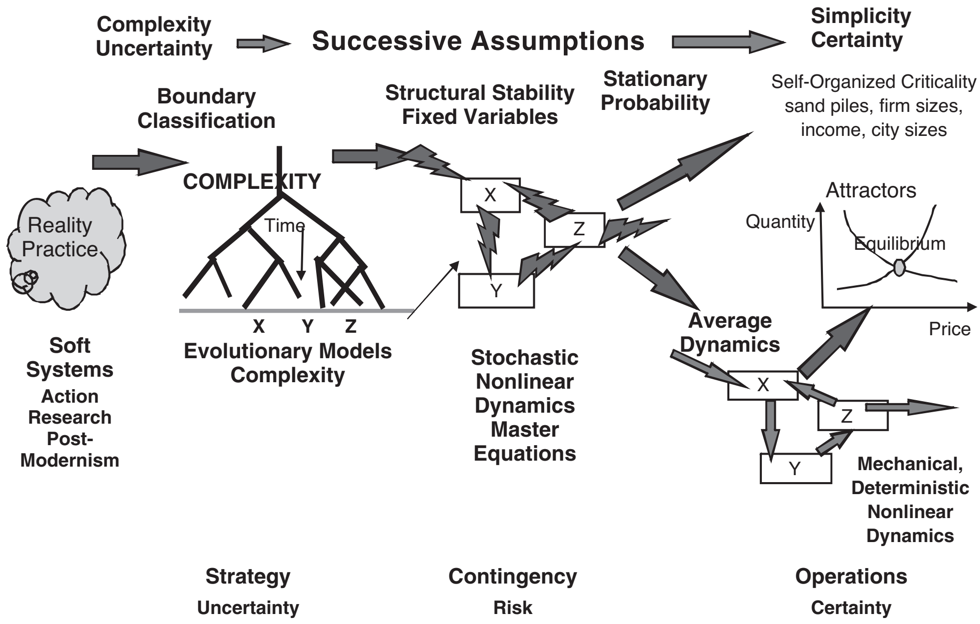

Figure 1.1 Successive assumptions that lead to various 'scientific' understandings of a situation

situation, the inherent openness of the future is constrained by two basic assumptions:

- the closure of the system to unknown outside influences; and
- the homogeneity and fixity of the classes of internal elements.

If these two assumptions can reasonably be made, then in fact the system may well behave in a predictable way. It really reduces to saying that providing nothing new happens in the environment and that system elements continue to act as they have been, we can predict the future. However, such an approach may work for artefacts that are only used in environments for which they were designed, but not for living things which can learn, get bored and be creative. Also, even the first assumption implies that all the interactions between system and environment are known and held within given bounds. But in reality, our system is an 'intellectual construction' which captures some, or many or most of the interactions between it and the environment but is constrained by the bounded rationality imposed by the modeller: it does not include the things that the modeller does not know about, or considers to be irrelevant. Indeed, it is through events and crises that some of the things we did not know will reveal themselves.

The assumptions are specifically shown in Table 1.1.

If we are interested in understanding the behaviour of the existing system then we can simply take the inventory and description now, and consider the 'working' of the components, bearing in mind the way that different aspects and elements are connected. This assumes structural stability and takes us away from open, evolutionary change, to the effects of running a fixed set of processes.

By considering only the present and assuming structural stability of our current system, we can generate models that govern the dynamics of the probability distributions of the different variables. Such models are

Table 1.1 The general complexity framework

Number	*Assumption made*	*Resulting model*
1	Boundary assumed	Some local sense-making possible – no structure supposed.
2	Classification assumed	Strategic, open-ended evolutionary – structural change occurs. Statistical distributions part of the evolutionary process can be multi-modal.
3	Average types	Operational, probabilistic, nonlinear equations, master equations, Kolmogorov equations – assumed structurally stable. Statistical distributions can be multi-modal or power laws.
	First pathway	
4	Statistical attractors	Self-organized criticality, power law distributions.
	Second pathway	
4	Average events, dynamics of average agents	Deterministic mechanical equations, system dynamics – assumed structurally stable. No statistical distribution.
5	Attractors of nonlinear dynamics	Study of attractors, catastrophe theory. Nonlinear dynamics with point, cyclic or chaotic/strange attractors.

systems models that are very useful in studying the resilience and risk of collapse of organizations or structures as a result of fluctuations in the environment and within the system. These models take into account not only the 'average' dynamics of such systems but their different possible futures in which luck can play a positive or negative influence. In other words, such models can consider how some particular shock or internal event may disturb the behaviour of the system, taking into account all possible sequences of events – including those that are possible but improbable. Resilience and contingency planning is not just about how a system will respond to a particular shock or disturbance but the relative probabilities of different possible pathways into the future – some corresponding to a return to normal functioning and others to different kinds of failure or collapse.

This is the essence of calculating risks and attempting to design systems that are resilient and capable of dealing with possible events and fluctuations. Such applications are of great importance for logistics, supply and demand networks and production systems. Systems models can be developed that can be used to examine their performance and also their resilience and the risk of failure under various circumstances. Structural stability and essentially fixed structural elements can be assumed if, for example, the systems are designed and owned by single agents. Of course, if the different elements should be managed by different agents with their own motives and learning capacity, models can be used to explore the effects of different assumptions of what these might be. In any case, these probabilistic dynamic models have been developed in the natural sciences and can be applied to help explore, design and make decisions in human complex systems.

If the events considered are discreet, then the running is according to a probabilistic dynamics, and we have what is called stochastic nonlinear dynamics, where different regimes of operation are possible, but the underlying elements never change nor learn, nor tire of their behaviours.

In Table 1.1 we have set out two pathways to greater simplification and easier understanding. The first pathway is to assume that we can use average rates instead of probabilities for the events, in which case we arrive at deterministic system dynamics. This is in general, nonlinear dynamics and may be cyclical or chaotic or at equilibrium, but what happens is certain, simple and easy to understand.

The second pathway is to suppose that the dynamic probabilities move rapidly to equilibrium – to a stationary distribution. This is a particular way to define a 'system' since it is one in which the interactions are assumed to maintain the form of the distribution. The work of Bak on sand piles led to the idea that this stationarity expressed that the system attained a self-organized criticality. So, for example, the probabilities of earthquakes, or of cities or firms of different sizes is considered to result from systemic interactions that will tend to restore the stationary distribution should it be disturbed. For many years the work of Zipf on word frequencies and on city sizes showed from the data that the distribution in question was particularly simple – a seemingly fixed negative power law governing the probability of finding a city of a given size. The US distribution of city sizes for example between 1790 and today has been described by a Zipf exponent of varying between 0.98 and 0.75 which is a remarkably stable curve. However, this apparent stability hides a great deal of dynamics since individual cities have occupied very different places in this scheme. Similarly, for firm sizes, although the overall curve for US firms is fairly stable the fate of each individual firm is still quite dramatic ending of course, as all things must, in extinction. While these ideas are interesting it is difficult to see how management can use these results in any way to make decisions. Rather it is true that agents struggle to attain their ends whatever that may be, and the interactions of the system seem to enmesh them in a fairly stable collective outcome. However, recently Toyota overtook General Motors as the largest automobile producer and so the distribution is in fact populated by large amounts of dynamic change and the probabilistic nature of the distribution by no means reduces agents to impotence. Bad management or lack of effort will simply hasten the demise that is the overall outcome that the distribution promises.

This discussion exposes some of the limitations associated with the assumptions of structural stability, equilibrium assumptions and the use of average types and distributions to describe system properties. In the next sections we look at how systems thinking in the second part of the twentieth century shifted away from assumptions of structural stability to focus on the dynamics of open, out-of-equilibrium systems and the importance of microdiversity in heterogeneous populations.

THE SCIENCE OF COMPLEX SYSTEMS: COMPLEX ADAPTIVE SYSTEMS

The later part of the twentieth century saw a questioning of the popularity of centralized, hierarchical management control, accompanied by a growing concern about the unintended and unforeseen consequences of planned management interventions.

Herbert Simon's articulation of bounded rationality in decision making and Mintzberg's articulation of strategy as emergent (Mintzberg, 1978) were important milestones in management thinking. Both pointed to the limitations of the planned approaches of decision makers in ensuring expected outcomes of management action, and fuelled the search for alternatives to the design paradigm.

As early as 1957, Simon highlighted the limitations in informational and cognitive scope and capacity of managers to make optimal decisions in complex situations, due to bounded rationality:

> boundedly rational agents experience limits in formulating and solving complex problems and in processing (receiving, storing, retrieving, transmitting) information. (Simon, 1957)

Simon's work was perceived at the time as a challenge to develop better optimization techniques within the design paradigm, but in fact it pointed to the more profound issue of whether it was *ever* possible to develop an optimal plan.

By marking the distinction between planned strategy and strategy in action Mintzberg's concept of emergent strategy highlighted the contextual complexity for strategic action. He proposed that *actual* strategies *emerge* from the *dynamics of interaction* between the organization and its environment. This idea brought with it notions of organizational learning and evolution over time. In the organizational behaviour literature, there was a growing interest in the role of self-organizing groups and front-line inventiveness in enabling transformation and innovation whilst maintaining organizational integrity in dynamic competitive contexts.

The rapid adoption of the Internet and related technological advances in the 1990s highlighted the networked nature of society and economics, characterized by increased informational complexity and scope for greater uncertainty and unpredictability associated with the consequences of management action. The global inter-connectedness and network dynamics made it difficult to define the requisite system boundary and parameters of structural stability within the deterministic design paradigm (Merali and McKelvey, 2006).

These developments generated the interest of management scholars in the 'new' science of complex systems which enabled the formalization of ideas of adaptation, emergence, self-organization and transformation.

Self-organization, emergence and adaptation

In systems thinking the idea of emergence was originally expressed in the context of systems as hierarchical, nested systems of systems – the philosopher C.D. Bond coined the term 'emergent properties' for properties that emerge at a certain level of complexity but do not exist at lower levels (Capra, 1996). Scientists in the second half of the twentieth century brought to the fore the importance of the open nature of systems and provided insights about the dynamics of emergence, inspiring management scholars to develop models of organizations as complex adaptive systems. Complex adaptive systems are systems that adapt and evolve in the process of interacting with dynamic environments. Adaptation at the macro level (the 'whole' system) is characterized by emergence and self-organization based on the local adaptive behaviour of the system's constituents.

Three of the most influential developments in systems thinking about emergence and self-organization in open systems came from the physical and life sciences: Prigogine's work on dissipative structures in chemical systems along with Eigen's hypercycles and Haken's articulation of Synergetics, Maturana and Varela's concept of autopoiesis in living systems, and the articulation of evolutionary dynamics in artificial life and ecosystems. All of these highlight that self-organization is not the result of *a priori* design, it surfaces from the interaction of system and the environment and the local interactions between the system's components. This capacity for the spontaneous *creation* of order through *intrinsically* generated structures is captured in Stuart Kauffman's (1993) expression 'order for free', in the notion of Prigogine's dissipative structures (Prigogine, 1967), Haken's Synergetics (Haken, 1973), Eigen's hypercycles (Eigen and Schuster, 1979) and in Maturana and Varela's theory of autopoiesis (Maturana and Varela, 1973).

Dissipative structures, autocatalysis and synergetics

In the 1960s Ilya Prigogine and his colleagues demonstrated that energy input to an open system with many interacting components, operating far from equilibrium, can give rise to a higher level of order. Running a particular chemical reaction where nonlinear catalytic effects were present gave rise to the spontaneous formation of stationary or moving patterns of colour ('dissipative structures') that either maintained themselves in a stable state far from equilibrium, or evolved to produce new patterns.

Close to equilibrium the chemical kinetics can be described by the linear equations of classical thermodynamics, but as the chemical reaction is driven further from equilibrium by pumping in reactants, the system reaches a critical point at which it 'jumps' spontaneously from homogeneity to a moving or stationary coloured pattern. Prigogine modelled this phenomenon using nonlinear chemical kinetic equations receiving matter and energy from the outside. In this explanation, changes in the internal structure (observed as instabilities and the jump to the new structural form) are the result of local fluctuations in the densities of chemicals amplified by positive feedback loops. He called the emergent, ordered structures 'dissipative structures'.

Also in the 1960s Herman Haken developed his science of *Synergetics* (Haken, 1973, 1978), based on his work with lasers, demonstrating the self-organization of an incoherent mixture of lightwaves of different frequencies and phases into a coherent laser light of one single monochromatic wavelength. The synergetic mechanism was taken up by Beer in his formulation of Syntegrity as a method for team-based problem solving (Beer, 1994).

In the 1970s Manfred Eigen speculated that the origins of life may lie in interacting autocatalytic cycles (hypercycles) that evolved by passing through instabilities and creating successively higher levels of organization characterized by increasing diversity of richness of components and structures for natural selection to act on.

Prigogine, Eigen and Haken's discoveries of self-organizing systems are all characterized by:

- stable states that are far from equilibrium;
- development of amplification processes through positive feedback loops;
- the breakdown of stable states through instabilities that lead to new forms of organization;
- continual flow of energy/matter through a system; and
- mathematical description in terms of nonlinear equations.

As Capra (1996) points out, in nonlinear thermodynamics the 'runaway' positive feedback loops that had always been regarded as *destructive* in cybernetics now appear as a source of new *order* and complexity in the theory of dissipative structures.

Dissipative structures demonstrated how self-organization and the emergence of structures (such as oscillating colours, spiral waves, etc.) at a completely different level to that of the molecules creating it, could occur spontaneously. The patterns were in the range of centimetres while the molecules that formed them were of the order of a hundred million times smaller. All that was required was a system of interacting elements (in this case molecules and atoms) that are open to flows of energy and matter. This gives us a science that includes history both in the organization and structure that has emerged, together with its relationship with the environment: in the words of Prigogine and Stengers: *'where classical science used to emphasize permanence, we now find change and evolution.'*

The nonlinear equations that describe the system's dynamics have a number of possible solutions, and the path that the system takes will depend on the system's history and the prevailing environmental conditions at that precise moment. As the system is in a constant state of flux, the combination of system state and environmental conditions is unique for each dissipative structure, and this means that over the longer term it is *impossible* to predict what the next system state will be.

It is this impossibility of prediction that distinguishes complex adaptive systems from chaotic systems. The term 'chaos' has been popularized in the managerial literature on dynamism, innovation and creativity, and is often used to refer to a state of disorder and randomness out of which arises a new order. However, technically a chaotic system is a *deterministic* system that has parts of its trajectory that are not stable so that its future is very sensitive to its precise path and current state. In practice the degree of accuracy (of measurement of start conditions) needed in order to predict an outcome is likely to be impossible to obtain. Chaotic systems share properties with complex systems, including their sensitivity to initial conditions. However, in the study of chaotic systems, the systems' dynamics are generally described by a small number of variables interacting in a nonlinear fashion, whilst complex systems have many degrees of freedom.

The scientific study of open systems has led to the science of complexity – that is the science of evolutionary change, adaptation and self-transformation. It deals with systems that can undergo spontaneous, symmetry breaking transformations corresponding to qualitative change with new emergent features, capabilities and processes and do not simply grow or decline within a fixed set of dimensions. It is easy to see the appeal of such a science for those in search of systemic principles to explain the dynamics of socio-economic systems: it has the potential to address the ideas of path dependency, creativity, disruptive change, unpredictability and self-determination that are characteristic of human activity systems.

This approach for open systems presented a major contrast to the equilibrium dynamics of traditional Newtonian physics, and brought to the fore the importance of system/environment interactions. For management scholars it suggested the possibility of a novel paradigm for the organization of complex social systems – one in which individuals did not have sight of the whole problem space, there was no central co-ordinator, and yet their local interactions resulted in the emergence of a coherent collective behaviour in the face of environmental perturbation. We shall see the impact of these ideas on current thinking about competition and the evolving competitive landscape in a later section.

Autopoiesis

Whilst the discovery of dissipative structures in the natural sciences provided the conceptual frame for understanding the dynamics of self-organization and transformation, the biological sciences provided a novel perspective on sustainability, life and the maintenance of organizational integrity.

The cybernetic movement had already launched a stream of research on the development of machine intelligence, and von Neumann's work with cellular automata forms an important component of experiments with artificial life to the present day. The von Neumann machine was a theoretical machine which, by following precisely detailed instructions, could fashion a copy of itself. The concept was then improved when Ulam suggested that the machine be built as a collection of cells on a grid. The idea intrigued von Neumann, who drew it up – creating the first of the devices later termed cellular automata.

Maturana and Varela's theory of autopoiesis had its roots in the cybernetic world: they examined the mathematical models of self-organizing networks from cybernetics, and using cellular automata, they developed the model of self-producing organization that is at the heart of their theory. Maturana and Varela (1973) identified *autopoiesis* (self-production) as the defining characteristic of all living systems. The term is sometimes used in a more general sense to refer to self-organizing systems with nonequilibrium dynamics capable of maintaining stability over long periods of time.

According to their definition, the system is open to the flow of energy and materials, but maintains its integrity and identity by organizational closure:

> Living systems [are] organised in a closed causal circular process that allows for a change in the way the circularity is maintained, but not for the loss of the circularity itself.

In keeping with the cybernetic tradition, their definition distinguishes between the organization (abstract description of pattern of relations) and structure (physical relationships between components, physical embodiment of its organization). They define the living system as a network of networks of (self-producing) production processes, identifying three types of relations (*relations of constitution*, *relations of specification* and *relations of order)* that must obtain between components in order to maintain the substance, form and integrity of the autopoietic *unity* over time. The autopoietic *unity* is a self-referential, self-regulating, self-producing, self-organizing entity capable of maintaining a stable state under nonequilibrium conditions. The autopoietic 'network of processes of production' is realized by components interacting with each other through structural coupling and neighbourhood relations of variable strength. Perturbations in the environment are sensed by boundary components and appropriate adjustments are propagated through the network. Individual components make adjustments relative to their local neighbourhood relations to maintain a stable global *organization.*

The mechanism of structural coupling allows the system to learn and to generate new behaviours in response to environmental changes whilst preserving its overall pattern of network relationships. The system interacts with both its internal and external environment through structural coupling, responding to environmental changes with structural changes which will in turn alter future behaviour of the system as a whole.

In the management field, autopoiesis has provided an important conceptual framework for thinking about boundary phenomenology and the processes of self-organization that allow learning and creativity whilst maintaining organizational integrity and identity in the face of environmental perturbations (Merali, 2002).

In sociology Niklas Luhmann developed the theory of autopoiesis to study social systems as networks of networks of communication:

> Social systems use communication as their particular mode of autopoietic reproduction. Their elements are communications that are ... produced and reproduced by a network of communications and that cannot exist outside of such a framework. (Luhmann, 1990)

The dynamics of the system is defined in terms of self-amplifying feedback loops, and network closure gives a shared system of beliefs, explanations and values – a context of meaning – which is continually sustained by further conversations. In Luhmann's approach, communication acts include self-production of roles and boundaries (of expectation, confidentiality, loyalty, etc.), which are maintained and renegotiated by the autopoietic network of conversations.

The autopoietic construct illustrates the combination of path dependency and innovation that have characterized the evolution of systems thinking: in it we can see clearly the connection between the cybernetic movement of the Macy conferences, and the self-organizing principles of complex systems science articulated by Prigogine, Eigen and Haken. Its impact on the field of management has been largely at the conceptual level – as metaphor, model and, as in Luhmann and Merali, theory for making sense of the systemic properties of individual organized forms and their persistence.

In the next section we look at the ideas about the way in which other ideas from biology have contributed to our understanding of more complex socio-economic systems involving multiple relationships between many individuals and organizations – we move from looking at the *unity* as an individual persistent, bounded entity to looking at populations of different entities and their co-evolution with the changing landscape.

Adaptation, evolution and co-evolution

In the second half of the twentieth century a number of models and theories developed to link diversity of individuals at the local micro level with population level effects at the macro level. Some of the main contributions to systems thinking in this vein came from models of evolutionary dynamics and the creation of artificial life with cellular automata.

Artificial life

Simulations deploying von Neumann's cellular automata were instrumental in the development of ideas about the way in which a collection of simple entities (later referred to as 'agents')[4] could, by following very simple interaction rules, self-organize into complex structures. This type of modelling was used extensively in the 1960s and 1970s to develop ideas about the origins of life and the organization of biological systems at all scales, ranging from the genome and cellular organization through to organisms, ecologies and social systems.

Craig Reynolds work on the dynamics of flocking was amongst the first biological agent-based models that contained social characteristics (Reynolds, 1987). He tried to model the reality of lively biological agents, known as artificial life, a term coined by Christopher Langton in the 1980s. Models such as these (in which elaborate, stable flocking patterns emerge as individual agents follow three very simple rules for positioning themselves relative to their neighbours) inspired management scholars to look for simple rules that they could deploy to create a self-organizing, adaptive workforce. Experiments showing the spontaneous emergence of novel artificial life forms encouraged them to advocate the organizational forms that were on the 'edge of chaos', aligned with Kauffman's speculation that:

> Networks on the boundary between order and chaos may have the flexibility to adapt rapidly and successfully through the accumulation of useful variations. In such poised systems, most mutations have small consequences because of the systems' homeostatic nature. A few mutations, however, cause larger cascades of change. Poised systems will therefore typically adapt to a changing environment gradually, but if necessary they can change rapidly. (Kauffman, 1991)

Whilst many of the attempts to translate these ideas into management practice were overly simplistic, this strand of work succeeded in providing management scholars with models for conceptualizing the dynamics of self-organization.

Evolutionary dynamics: fitness landscapes

According to the classical theory of evolution, populations adapt to their environment under the pressures of selection. At the individual level, biological fitness is determined by the genetic make-up of individuals, with those that have a good enough fit with the environment surviving to reproduce.

The classical top-down perspective of selection as the driver of evolution has been complemented by complex systems scholars using cellular automata to define mechanisms for the generation of micro-level diversity and defining the 'fitness landscape' or map of the relative value (for survival) of individual genetic endowments. The most common mechanisms for generation of diversity are random mutation and recombination. The evolutionary process is defined as a search in the space of possible genotypes for points that map for a higher fitness. The best known of such models is Stu Kauffman's *NKC* model in which the space of possible genotypes is defined by a network of *N* genes (with *A* possible variants (alleles)) with *K* interdependencies between them (determining the extent to which the potency of each gene is affected by its interacting others) and affected by *C* external interdependencies. As Maguire et al. (2006) explain:

> biologists conceptualize the challenge facing species as a problem of combinatorial optimization – of navigating the landscape in search of higher peaks by sampling points in the space, ascertaining the associated fitness, and moving – then theorize about adaptation, competition and co-evolution using computational experiments. Agents thus, try to climb toward fitness peaks, but run the risk of getting trapped on suboptimal ones.
>
> It is also important to realize that since a new behaviour can have emergent properties and features, in reality the 'fitness landscape' only exists where it is 'populated'. The real fitness, and even the dimensions of performance may change when a new type is actually tried out.

Models of evolutionary dynamics have been deployed in management science as a mechanism for connecting the diversity and interactions of individuals at the local level with the overall system characteristics displayed at the macro-level for a number of different applications including the dynamics of competition, the emergence of dominant designs, the impact of disruptive technologies and organizational adaptation.

Evolutionary drive

'Evolutionary drive' was put forward some years ago (Allen and McGlade, 1987) as the underlying mechanism that describes the change and transformation of complex systems. In this view evolution is driven by the interplay over time of processes that create micro-diversity at the elemental level of the system and the selection operated by the collective dynamic that results from their interaction together with that of the system with its environment.

This co-evolution is seen as a continuous, on-going process and not one that has already 'run its course', as in the case of 'evolutionary stable strategies' (Maynard-Smith, 1982). Because of the ignorance of individuals, and of the universe itself, as to the pay-offs that will occur over time for a given behaviour, there are always new aspects of micro-diversity that can occur, so that co-evolution never reaches an 'optimal' outcome, as in the Game Theory approach. Instead, we see this multi-level exploration and retention process as an on-going process that is occurring in real time, enabling the system to respond to currently undefined changes in the environment. History is still running. Each behavioural type is in interaction with others, and therefore evolutionary improvements may lead to greater synergy or conflict between behaviours, and in turn lead to a chain of responses without any obvious end. And if there is no end, then the most that can be said of the behaviour of any particular individual or population is that its continued existence proves *only that it has been 'good enough' – but not that it is* optimal.

In this review of the ideas that link complexity to the management of organizations the guiding premise is that successful organizations require underlying mechanisms that continuously create internal micro-diversity of ideas, practices, schemata and routines – not that they will all be taken up, but so that they may be discussed, possibly tried out and either retained or rejected. It is this that will drive an evolving, emergent system that is characterized by qualitative, structural change.

It firmly anchors success in the future on the tolerance of, and ultimately organizational understanding of, seemingly unnecessary perspectives, views, and ideas, since it is through the future implementation of some of these that survival will be achieved. In other words the organizational behaviour and the functional types that comprise it *now*, have been created from the competitive and/or cooperative interactions of the micro-diversity that occurred within them in the *past*.

Elements may be of the same type, but differ from each other in detail. Nobody may know whether these differences will make a difference as they are just random variations around a reasonable average. But, consider that there is in fact a 'fitness' landscape which actually reflects better and worse 'fit' of the diverse individuals to the environment. In biological evolution, the variation is caused mainly by genetic and epigenetic variations which lead to phenotypic heterogeneity for which the fitness landscape will provide differential survival and reproduction rates, thus defining and amplifying the 'fitter', and suppressing the less fit. In this way, the existence of mechanisms that provoke genetic and phenotypic variation will automatically produce the exploration of the fitness landscape.

In a competitive market it will be true that differential performance will be defined by customers and investors through the choices they make. Within organizations, however, evolutionary change will require that different performances of different individuals, ideas, practices or routines be noticed, and that what works well is deliberately reinforced, and what works less well discouraged. This differential dynamics is really the 'selection' term of Darwin, operated by the environment, the customers and investors of the market place, or by the beliefs of the upper echelons of the organization. The organization chooses between different possible practices, routines, etc. and the market chooses between different possible products and services made by firms – and the only thing that is certain is that if there is no diversity to choose between, then nothing can change.

Evolution can only occur if there is something that will generate heterogeneity spontaneously. And this is in fact the current ignorance about future outcomes and a lack of commonly agreed norms of how things should be done. This leaves managers with the challenge of deciding how much diversity to support within the organization for the sake of an unknowable future: the real options approach is designed to allow managers to invest in possible futures, but deciding *what* to invest in is still a challenge. The situation is further complicated by its dynamics and the coupling of the internal organization and the environment: the shape of the competitive landscape changes as individual organizations make their moves, and, depending on the dimensions of change, the fitness factors may also change. This brings to the fore the importance of time and timing, and of the information flows between system and environment.

We can devise a simple computer program to demonstrate the dynamics of evolutionary drive, by considering a population that initially sits at a low point of a fitness landscape, and then has random variation of individual fitness. Different individual types will grow at different rates, thus defining 'fitness' after the fact. Gradually the population will 'climb' the local fitness landscape because of processes of 'exploration' in character space. Ignorance and consequent randomness are very robust sources of such exploration. Clearly random changes in the design of any complicated entity will mean that tinkering experiments will lead to many non-viable individuals and hence that there is an 'opportunity cost' to behavioural exploration. By considering two populations simultaneously at the foot of the fitness hill, where one population has a higher rate of randomness in character space than the other, we can compare the relative success of different rates of exploration. Initially, the 'explorer' population wins, because, despite its cost in nonviable individuals, diffusing and innovating faster is rewarded by the fitness slopes it discovers. Later, however, when the landscape has been explored and climbed, faster diffusion is no longer rewarded and the more conservative population with less exploration eventually dominates.

Evolution is thus driven by the noise to which it leads. Providing that microscopic diversity (noise) is produced in systems of interacting populations, the interaction dynamics will lead to the retention and amplification of some, and the suppression of others. This process will determine the 'ability to evolve' as well as the particular types of micro-diversity contained in the populations at a given time. This situation reinforces the earlier epistemic theme of our limited knowledge of our own systems. There will never be a completely clear understanding of any evolving system at a given time, because it will always contain micro-diverse elements that may or may not turn out to be successful. The understanding that we can have of reality is obtained by creating a 'system' of interacting entities that are sufficiently correct to describe the current situation, but inadequate to predict the future structural evolution that may occur.

However, understanding the nature of evolutionary dynamics enables us to speculate on the space of possibilities for the future by experimenting on how plausible models of current states may play out under a variety of future conditions.

For a social system, the irreducible uncertainty of the open-ended co-evolution of things means that a messy, micro-diversity is the only insurance against an unknown future, and that social evolution will proceed through successive periods of drift and diversification separated by shorter spans of selective elimination. Evolution and co-evolution only demonstrate what is not viable at a particular time, and do not imply that what remains is an optimal structure that achieves anything in particular. Models can be built that capture the behaviour of multiple interacting individuals and the way in which their beliefs are confounded, reinforced or updated as they struggle to make sense of their changing circumstances. Complex systems models can therefore help us explore the consequences of different possible practices, values and beliefs, perhaps indicating some basic features that will underlie any functioning society.

Modelling complex social systems

Advances in mathematics of complex systems since Newton and Leibnitz' differential calculus have become increasingly sophisticated, and significant developments include statistical mechanics, dynamical systems theory for dealing with nonlinearity, feedback and iterations, and Poincare topology and fractal geometry for studying the qualitative features of complex systems. Whilst analytic methods have always been used for studying system dynamics, most nonlinear equations for complex systems are too difficult to solve analytically, and the advances in computing capacity have advanced the practice of solving by just running them numerically.

Cellular automata and agent-based systems are the most prevalent modelling approaches used for modelling complex social systems. One of the earliest social agent-based models (ABM) in concept was Thomas Schelling's segregation model (Schelling, 1971). Though Schelling originally used coins and graph paper rather than computers, his models embodied the basic concept of ABMs as autonomous agents interacting in a shared environment with an observed aggregate, emergent outcome.

With the growing availability of computers ABMs could become much more ambitious (an early example is Robert Axelrod's model for competing strategies for the Prisoner's Dilemma).

For social systems ABMs have been used to examine phenomena from the societal scale (e.g. ethnocentricism and dissemination of culture and the co-evolution of social networks and culture), issues as designing effective teams, understanding the communication required for organizational effectiveness and the behaviour of social networks at the level of the individual organization (Axelrod, 1997; Carley, 2003). More recently, agent-based simulations have been based on models of human cognition, known as cognitive social simulation (Sun, 2006). The exploitation of ABMs in the management field spans applications in the strategic, operational and organizational domains (Lomi and Larson, 2001; Maguire et al., 2006).

The diffusion of agent-based modelling has been accelerated by the availability of specialized modelling software (StarLogo in 1990, SWARM and NetLogo in the mid-1990s and RePast in 2000). A number of special interest groups and journals have been established focusing on the use of agent-based modelling in the social sciences (reviewed in Bonabeau, 2002; Samuelson, 2005; Samuelson and Macal, 2006).

Epstein and Axtell developed the first large-scale ABM, the Sugarscape, to simulate and explore the role of social phenomenon such as seasonal migrations, pollution, sexual reproduction, combat, and transmission of disease and even culture.

Learning multi-agent models

Agent-based modelling really become complex systems modelling when the agents are open to new ideas (decision behaviours) and can learn over time. This effectively opens the system. Without this, the models themselves are still closed, mechanical systems.

One of the direct uses of ABMs with learning agents is in the study of competitive dynamics. The competitive landscape of a given organization consists, among other things, of other organizations with similar objectives, and so there will be two criteria for fitness: (1) the ability to out compete similar organizations, or (2) the ability to discover other 'niches' which can still command resources, but which escape the competition.

In Darwinian thinking the micro-diversity of agents that occurs is considered to be 'random' and independent of the selection processes that follow, while in human innovation we like to think that there is intentionality, calculation and belief that may, *a priori*, 'channel' diversity into some narrower range.

The openness of an organization to its environment underlines the importance of the 'fit' between an organization and its environment. The 'fitness' of any organization or structure is a measure of its ability to elicit, capture or merit resources from its environment and put them to use for self-perpetuation. In order to maintain 'fitness' in a changing environment then, it will be necessary for the organization to be capable of actively transforming itself over time, requiring that agents change their internal knowledge, behavioural rules and perhaps connections.

Just having noisy agents, or signals with agents with fixed rules, which can be simply described by fixed stochastic equations corresponds to a mechanical model of social systems. Representing learning agents that can give rise to structural change and emergent capabilities takes us from a mechanical model with fixed structure to evolutionary and co-evolutionary models which exhibit full complexity.

The dynamic perspective on competition shifts the emphasis from creating a set of maximally efficient operations that will produce some good or service for a particular market, to developing adaptive capacity in recognition of the reality of openness. Openness exposes the organization to change in supply and demand situations and the continual appearance of new ideas, technologies and competitors. This in turn demands changes in the organization itself, as it is presented with the need to learn and adapt, continually shifting its focus to track change. This discussion of organizational dynamics reinforces the replacement of maximal efficiency with 'sufficient efficiency' combined with sufficient adaptability, but emphasizes the significance of self-organized, organizational change in underwriting this process.

The problem of what constitutes the requisite level of efficiency and diversity to deal with the changing competitive landscape has no single definitive solution, but the use of agent based models allows us to explore the space of possible futures that may evolve from the (albeit limited) set of endowments and actions that we can conceivably attribute to our agents.

CONCLUSION

The evolution of systems thinking, starting from the ancients' distinction between structure and form, has progressed as successive simplifying assumptions have been challenged and new dimensions have been introduced.

Associated with each stage of development are concepts that have influenced management thinking along with powerful methods and models for adoption in management practice. In this chapter we have traced the path from approaches predicated on assumptions of structural stability to the present day engagement with complex systems science and the nonequilibrium dynamics of open systems.

One of the key transitions in the methodological perspectives between the two halves of the twenty-first century has been the shift from assuming structural stability to questioning whether and when it is safe to assume structural stability. In the absence of structural stability the challenge shifts from being one of dealing with uncertainty to one of also dealing with unpredictability.

The science of complex systems has given us the conceptual and methodological equipment to tackle issues of emergence, self-organization, evolution and transformation, to elucidate the mechanisms by which micro-level properties can give rise to macro-level behaviours, and to explain the generation of novel structures and behaviours over time.

The developments in evolutionary dynamics have challenged two other methodological constructs that dominated systems thinking in the earlier era. The emphasis on open systems and the concept of co-evolution have entailed re-thinking the construct of the boundary and the separation of concerns between system and environment. The recognition of micro-diversity, outliers or 'noise' in the generation of alternative evolutionary pathways has challenged the use of average values to define variables, and this in turn has challenged the relevance of many of the statistical approaches for modelling the dynamics of social systems.

Historically systems' thinking has its roots in philosophy and the natural and biological sciences. The application of systems concepts to social systems has been an important component of management science. The scientific understanding of the being and becoming of biological and physical systems has been variously deployed in the management field as metaphor, analogue and true description of social systems.

Some of the objections to using concepts from the natural sciences to explain human social systems have focused on the inadequacy of these concepts to deal with issues of free will, intentionality and purposiveness. However, the recognition exists that there are collective phenomena and systemic properties that can be ascribed to human activity systems. Systems' thinking gives us the possibility of choosing and using abstractions to make sense of the dynamics that underpin the behaviour of individuals and collectives. Complex systems thinking is attractive because it gives us the concepts that have been used to characterize social behaviour in the human sciences (e.g. emergence, adaptation, evolution, transformation, path-dependency, learning, diversity, serendipity), and allows the possibility of developing models that capture some of the richness and diversity of human existence. The complex systems modelling approaches allow us to experiment with possible worlds in which consequences of our actions play out over time. In doing so we need to be aware of the dangers of bounded rationality and its influence on the choices that we make about the abstractions we deploy, and the assumptions we make about the data that we test these against.

Over time the focus of systems' thinking has shifted from structure (reflected in the use of modularization to deal with complexity), to organization or form (accentuated in the cybernetic approaches) to the network dynamics of adaptation and transformation (within the paradigm of complex systems science). Each of these 'phases' has given us concepts, tools and methods for understanding and dealing with complexity in the world as we understand it.

For management science, systems' thinking is a framework that includes these different approaches and allows us to deal with the idea that the component parts of a system can best be understood in the context of relationships with each other and with other systems, rather than in isolation.

NOTES

1 Capra (1996) attributes the root meaning of the word 'system' with its holistic connotations to the Greek *synhistanai* (to place together).

2 For example, the Pythagorean distinction between matter and substance, and the Aristotelian distinction between *matter* and *form*.

3 For example, Heralcitus' observation that we cannot step in the same stream twice.

4 Whilst the origins of agent-based models go back to the von Neumann machine, it is probable that the first use of the word agent is by John Holland and John H. Miller's (1991) paper *Artificial Adaptive Agents in Economic Theory* which is based on an earlier conference presentation of theirs.

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2

Complexity Science and Organization

Raymond-Alain Thietart and Bérnard Forgues

INTRODUCTION[1]

Complexity science is the scientific study of systems with many interacting parts that exhibit a global behaviour not reducible to the interactions between the individual constituent parts. In less than twenty years, complexity science – as applied to social organization phenomena – has evolved from a small set of well-identified contributions to a rich field of varied research agendas and projects. The field is now characterized by epistemological, methodological and paradigmatic diversity. From the positivist stance of model builders to constructivist postures, from quantitative to qualitative methods of inquiry, from nonlinear dynamics to metaphors, this diversity makes complexity science as applied to organizations increasingly difficult to comprehend. In this rich field, fortunately, Maguire et al. (2006) provide an extensive literature review, which quotes no less than 331 references, and effectively gives order to the field. Building on Maguire et al.'s (2006) contribution our first objective is to revisit the order they propose. This will then serve our second objective, which is to reflect on the theoretical implications of complexity science for organization studies. In addition, and in contrast to Maguire et al.'s (2006) contribution, this chapter concentrates on what those authors term 'objectivist' work only, i.e. model-based approaches. What Maguire et al. term 'interpretivist' endeavours are left aside for two reasons: first, although we acknowledge their richness and relevance, we believe their metaphoric bent doesn't fit well with their objectivist counterparts, and this would hinder our theorizing; second, due to their richness, these endeavours merit an extensive treatment of their own.

Objectivist research applying complexity science to organization studies is concerned with understanding the processes by which complex, irregular interactions can achieve order, and those by which simple deterministic rules create complex phenomena that seem to be driven by chance. Organizations are viewed as comprising multiple actors with diverse agendas, internally and externally, who seek to coordinate their actions so as to exchange information, act, and interact in a nonlinear and dynamic fashion.

A series of observations from the study of nonlinear dynamics and complex systems is scientifically well established and relevant to our discussion. First, 'processes that appear to be random may be chaotic, revolving around identifiable types of *attractors* [i.e. a limited area in a system's state space from which it never departs] in a deterministic way'; the 'behavior of [these] complex processes can be quite sensitive to small differences in initial conditions'; and, '[c]onsequently, historical accidents may "tip" outcomes strongly in a particular direction' (Anderson, 1999: 217). Second, 'complex patterns can arise from the interaction of agents' and '[t]hese patterns are "emergent"' (Anderson, 1999: 218). Third, 'complex systems tend to exhibit "self-organizing" behavior' (Anderson, 1999: 218). These results stress the fact that deterministic systems can exhibit an apparent randomness that is nevertheless contained within a limited domain – a 'strange attractor' (Ruelle, 1991). They also highlight that, within this domain, behaviour is sensitive to initial conditions (Lorenz, 1963). Moreover, in situations of increasing returns (i.e. positive feedbacks), they are process dependent (Arthur, 1994). Furthermore, from random interactions between entities in a system, complex patterns may emerge (Holland, 1995). Finally, some systems, initially in a random state, can gradually self-organize to achieve an order (Nicolis and Prigogine, 1977; Kauffman, 1993) that is more than the aggregated interactions of the independent entities that make up the system.

In the following lines, we first give a brief survey of the contributions of objectivist complexity theories and draw relevant inferences for organization studies. The survey covers self-organization, deterministic chaos, path dependence, complex adaptive systems, and the selectionist contexts view. Second, we infer a set of propositions that serve as clues about how organizations work. Propositions are derived from the complexity theories we review and then relate to more 'traditional' organization theories. Finally, a last section concludes the chapter, drawing implications for organization research.

BRIEF REVIEWS OF MAJOR SCHOOLS OF THOUGHT IN COMPLEXITY SCIENCE

Self-organizing systems

Self-organizing systems theory, also known as autogenesis or synergetics (Haken, 1977; Nicolis and Prigogine, 1977; Prigogine and Allen, 1982; Kauffman, 1993) aims at explaining the emergence of order out of the interactions between entities such as DNA and RNA molecules (Kauffman, 1993), chemical elements (Prigogine and Stengers, 1984), and organizational actors (Drazin and Sandelands, 1992). Self-organization is a naturally emergent process of organizing found in dissipative systems that are subject to energizing forces. Order emerges as the result of interactions, induced by tensions that result from energy differentials between autonomous entities (Bénard, 1901). There is no specific overarching programme to create a given form of order. Rather, ongoing interactions may generate any form of organization. In the physical world, autocatalytic processes help to reinforce whatever order emerges. In organizations, order can result from learning processes by social agents looking for local solutions to problems. As a consequence, order may result from synergies among individual initiatives. Many debates have centred on the origins of self-organization. Once put into motion, entities within a system seem to adapt to the outcomes of their prior interactions. It is in the zone of instability, far from equilibrium, that changes take place, allowing some order to emerge. From a given initial state, dynamic interactions can lead to similar states as if systems entities were attracted to a preordained configuration. This is consistent with Prigogine and Stengers' (1984) argument, according to which a determined order is found only because it was there to be discovered in the first place.

Deterministic chaos

Chaos theory has received a considerable amount of attention in the natural sciences (Allen and Sanglier, 1978; Ruelle, 1991) and, more recently, in the social sciences (Brock and Malliaris, 1989; Cheng and Van de Ven, 1996). It emphasizes concepts such as sensitivity dependence to initial conditions (SDIC), process bifurcation, attractors, and irreversibility (Thietart and Forgues, 1995); and it is not concerned with agents *per se*. It represents a mathematical approach to the evolution of dissipative nonlinear dynamic systems characterized by low dimensionality. Interactions between simple relationships can evolve into a highly complex network, the behaviour of which is impossible to anticipate. Such systems can be stable, periodic in behaviour, or chaotic. The transition, or bifurcation, from stability to periodicity to chaos takes place when the coupling among forces of stability (i.e. negative feedbacks) and instability (i.e. positive feedbacks) increases. The coupling among forces can be changed by agency or when subjected to external shocks. Once put into motion, however, the combination of these forces can put the system on a route for which the end cannot be predicted. When in a chaotic state, behaviour is attracted and contained within a strange shaped frontier called a strange attractor (Ruelle and Takens, 1971). Within the attractor, even though behaviour is deterministically driven, prediction is impossible except for the very short term where sensitivity to small variations is not yet fully felt. These deterministic processes lead to surprising and unpredictable results. In fact, a small change, the effect of which is multiplied over time, can easily produce a dramatically different evolution. This theory has been applied to the study of organizational events such as innovation (Cheng and Van de Ven, 1996) and crisis (Thietart and Forgues, 1997). These studies show that what appears to be randomness is, in fact, deterministically driven. The succession and interaction of decisions create a very complex behaviour that develops a dynamic of its own based on actions or decisions taken by organizational agents. Paradoxically, freedom of choice appears to create its own determinism, but within which outcomes are impossible to predict precisely.

Path dependence

Unrelated to chaos theory – which is deterministic – path dependence is stochastic; but it is similar to chaos theory in its sensitivity-dependence characteristics. Positive feedback in economic systems illustrates the mechanism of path dependent evolutions (Arthur, 1990). According to Arthur (1990: 92) once chance opens up a particular path, it 'may become locked in regardless of the advantages of other paths' giving some firms a self-reinforcing initial advantage. Small perturbations, then, determine the pathway, which need not be the most efficient. These can tilt parts of the economy 'into new structures and patterns that are then preserved and built upon' and which are in part 'the result of historical chance' (Arthur, 1990: 99). In those situations described by Arthur (1994), an initial strategic advantage, which could be the result of the combination of past strategic choice and chance, is the 'cause' behind market domination. However, as noted by David (2001: 26):

> path dependent systems – which have a multiplicity of possible equilibria among which event-contingent selections can occur – may (...) become locked in to attractors that are optimal, or that are just as good as any others in the feasible set, or that take paths leading to places everyone would wish to have been able to avoid, once they have arrived there.

Perhaps the most famous case of path dependence is that of how QWERTY came to be the dominant keyboard arrangement (David, 1985). Arthur points to three characteristics which were crucially important in causing lock-in: technical interrelatedness (i.e. the need for compatibility among parts of a technical system); economies of scale; and quasi-irreversibility of investments. Path dependence has been extensively documented by organization scholars, as shown by the contributions in Garud and Karnøe's (2001) edited volume.

Complex adaptive systems

Complex adaptive systems, as is the case with self-organized systems theories, rely on an entirely different paradigm. Here the focus is not to search for simple causes to complex outcomes but, rather, to understand how simplicity emerges from complex interactions (Gell-Mann, 1994). In complex adaptive systems theory, simplicity arises from the aggregated behaviour of interdependent adaptive agents driven by a set of rules (Holland, 1988). Agents, following rules, adapt to each other and create an emergent order. A given set of rules governing interaction, a specified number of interacting agents and random events seem to uncover a 'hidden' process. Once in motion, the process follows a route towards a stable end, periodicity, or even apparent randomness. Ever since Conway's Game of Life (1976), successful and more comprehensive computer applications have developed in the field of organization studies: from the study of emergent social behaviour (Epstein and Axtell, 1996) to organizational adaptation (Carley and Hill, 2001), culture formation (Harrison and Carroll, 1991) and stock market evolution (LeBaron, 2000). In these models, emergent system-level behaviours are achieved through the interaction of agents. Stable patterns are not just the outcome of random encounters. Internal dynamics and random events coalesce to produce different orders by following multiple paths. Questions thus arise concerning the role of causation and the nature of the order that emerges, and in which chance plays a key role. The nature of the interaction itself, however, is deterministic; rules are fixed by choice or by nature. Once chance has opened up opportunities for viable alternative combinations, the system evolves towards an un-programmed, emergent order.

An emergent 'selectionist' contexts view

McKelvey (1997, 1999) provides an explanation for emergent order. New orientations, in the realm of organizations, emerge following random encounters of competencies which create something different from a simple arithmetic totting up. These encounters do not take place in an ordained manner, nor do they evolve in a completely disorderly manner. Through their interactions agents learn and adapt to each other to create something new. McKelvey (1997) likened organizations to quasi-natural phenomena, where human intentions and natural processes are intertwined. Top-down forces control bottom-up (i.e. naturally occurring) autonomous and innovative initiatives (McKelvey, 2004). In his view, organizational processes should be observed from a co-evolutionary perspective. Order, then, is the result of many 'Darwinian variation, selection, retention, and competitive struggle effects at different levels' (McKelvey, 1997: 360). Each emergent level becomes a selectionist context for the level below. Here, 'Darwin machines at a higher level operate to create order at lower levels; order that may be governed, in part, by simple rules' (McKelvey, 1997: 361). According to his theory, idiosyncratic intentions are present at a micro-level. However, 'micro-evolutionary order (…) emerges in the context of macro-evolutionary selection and competitive pressure' (McKelvey, 1997: 361). There is freedom to the extent that agents create the context for such encounters to unfold. There is determinism too, by virtue of the contextual forces. And there is chance in the interactions between agents. Once put into motion the emergent behaviour assumes a life of its own.

ORGANIZATIONAL IMPLICATIONS OF MAJOR SCHOOLS OF THOUGHT IN COMPLEXITY SCIENCE

In summary, if we accept that organizations are a function of complex processes, we can draw some tentative conclusions from the preceding review of complexity theories: (a) agency may create its own determinism (e.g. chaos theory); (b) chance can open up paths that inevitably lead to an inescapable outcome (e.g. path dependence view); (c) organizations are an emergent outcome, being the result of random encounters between agents that interact following a set of deterministic rules (e.g. complex adaptive systems and self-organization theory); and (d) order mostly emerges through a cascade of trial and error processes taking place at different levels (e.g. emergent 'selectionist' contexts view). These tentative conclusions stress each complexity science school's specific contributions. However, from their respective specificities, similarities and complementarities emerge. They all contribute to a better understanding of organizational dynamics. Some schools emphasize the process behind the dynamics of order creation; while others give an explanation of the forces at play in the process itself. We address each here.

Games scientists play: from Conway's Game of Life to NK *modelling*

Cellular automata (CA) and *NK* modelling are the most popular methods to simulate and study organizational phenomena. Cellular automata are best adapted to study emergence from spatial processes. They can represent social or economic dynamics, from competition to strategy (Sorenson, 2000). They can also help to investigate the evolution of populations of firms competing in a spatially delimited context (Lomi and Larsen, 1996). Interactions between agents are driven by simple and fixed rules. Each entity, a firm for example, interacts with its neighbours. Its state changes as a function of its neighbours' state. Conway's (1976) Game of Life research of the late 1990s and early 2000s, based on cellular automata, has provided interesting and counter-intuitive results. However, approaches based on cellular automata, limited by fixed rules and spatial constraints, have given way to more comprehensive and flexible approaches. *NK* modelling, for instance, was introduced by Kauffman (1993), who worked for a period at the Santa Fe Institute, to simulate biological evolution. Since then it has received many applications in organizational research. In *NK* models, we still have elements of a system in interaction, but the elements are not spatially bounded. The state of an element doesn't depend on distance criteria, i.e. the state of a neighbouring element. In *NK* models, *N* stands for the number of elements or attributes in a system, for instance, the organizational routines of a given organization (the system), as in Levinthal's (1997) research on firms strategies; while *K* is the interdependence between attributes, i.e. the coupling between routines in Levinthal's work. Through a 'random walk' the system evolves towards higher fitness on a metaphorically called 'terrain of adaptation' or 'fitness landscape' where the fittest configuration prevails. This modelling has received numerous applications since Levinthal's contribution, such as Gavetti et al.'s (2005) examination of analogical search strategies in novel industries; Siggelkow and Rivkin's (2006) work on innovation in multi-level organizations; Lenox et al.'s (2006) research on capability heterogeneity among firms; Levinthal and Posen's (2007) study of organizational adaptation and population selection and Porter and Siggelkow (2008) on the sustainability of competitive advantage. In addition, different but related methods such as genetic algorithms (GA, see Tracy, in this volume) can help researchers to investigate complex phenomena not directly accessible through empirical observation such as the evolution of organizational populations (Bruderer and Singh, 1996), the emergence of strategic groups in an industry (Lee et al., 2002) or innovation processes (Cartier, 2004). Applications of the coevolutionary *NKCS* model, on the other hand, are less frequent (for a review, see Vidgen and Bull, in this volume).

These contributions have opened new roads to researchers. Organizational scientists can now stretch their queries and investigate an organizational realm which would have been obscured by methodological hurdles or unavailability of data. These contributions are thus stepping stones to what McKelvey (2002) calls a model-centred organization science epistemology. They are tools to study complex phenomena; and are to complexity organizational science what mathematics is to physics.

From mechanics to magic: American versus European perspectives

McKelvey (2002) proposes a taxonomy of approaches within complexity science by distinguishing between American and European traditions – an ordering which clarifies the field and with which we agree. Specifically, the research questions addressed within each tradition aim at two different but complementary objectives. On the one hand, the 'American' tradition describes, through mathematical modelling and simulation, how complexity is created. On the other hand, the 'European' tradition gives an explanation of the forces behind complexity. In other words, one describes how order emerges from a disorganized world; while the other gives an explanation of the forces behind the search for order.

The works of Holland (1988) and Kauffman (1993) represent the American tradition well. Prietula (in this volume), for instance, reflects on this tradition linking complexity and computer simulation. Through computer simulation, he suggests that human adaptability and cultural history help maintain the stability of organizational structures. The 'Complex Adaptive System' (CAS) approach also illustrates this tradition. Through computational modelling and simulation, these and other scholars show that 'order' – i.e. an equilibrium or a recognizable configuration – appears when interactions reach a given intensity. When interactions are not intense enough, stability prevails. When interactions become too intense, they lead to a complete disorder. It is in the intermediate range, between too little and too many interactions, where emergent phenomena arise – at the edge of 'chaos'.

Agent-based modelling (ABM), along with the *NK*, GA, CA models previously discussed, is frequently used to study the successive transitions from stability to disorder and passing by an intermediate emergent state. It represents agents (e.g. individuals or organizations) or entities (e.g. decisions) that interact following fixed (or adaptable in the case of 'intelligent agents') rules. The outcome of these interactions is achieved 'mechanically'. It is the result of pre-established or adaptive rules mediated or moderated by some chance factor. In some instances, selection forces are at play and the search for optima occurs on a fitness landscape as in the case of *NK* and GA modelling. With such modelling, researchers explore the realm of the mechanics behind a dynamic process, which can lead to emergent phenomena and other forms of order.

The European tradition (Prigogine and Stengers, 1984; Mainzer, 1994), on the other hand, focuses on 'self-organizing systems'. First, it suggests an explanation of the forces behind self-organizing processes. Second, it gives a reason why some forms of 'order' (e.g. stability or sense-making regularity) appear. With respect to the forces driving the process dynamics, Bénard (1901) proposes that a tension, such as heat in his case, pushes the elements (molecules, agents, events) of a system to enter into interaction. An organizational equivalent would be the difference between supply and demand. The gap between supply and demand creates an adaptive price tension which gives rise to entrepreneurial initiatives or leads to industry re-organization. Due to this tension and for as long as it is maintained, interactions take place from which an 'order' can emerge. When tension reaches a given value, the system transitions from one state to another. A state of apparent stability can therefore lead to an emergent, self-organized outcome. From the emergent organized state, if tension increases, the system can then display ‘chaotic’ behaviour. Tension is maintained through a continuous inflow of energy to the system which dissipates and exchanges this energy with its environment. Without such tension nothing would happen and the system would remain stable.

A question remains: why a self-organized order? According to Prigogine, there is a self-organized order because it always was there to be discovered! Islands of order wait to be found in an ocean of ‘chaos’. Order originates from disorder. Disorder, induced by the tension, provides the ground for many trials and errors. However, a right combination doesn’t last for ever. A satisfactory fit between degrees of ‘complexity’ of encountering agents–elements–entities and degrees of complexity of the supporting context (Ashby, 1962) must exist. Without a satisfactory fit, self-organization couldn’t take place in the complexity regime of Ashby’s space (see Boisot and McKelvey in this volume). Once discovered, the fit – an emergent order – must be positively reinforced if it is to be maintained. Order is then kept under control through dampening and organizing forces that prevent the system from moving to a ‘chaotic’ state. The implications of this research programme for organizational research are particularly significant: while the European tradition doesn’t offer all the tools that the American tradition does, it – most crucially – provides clues about the ‘magic’ behind the process of emergence while proposing a teleological and dynamic perspective on complex systems evolution.

From God’s intention to Russian roulette: a pre-existing order versus a random quest

Some organizational forms and combinations work better than others. A timeless regularity in organizations, characterized by hierarchy, specialization, coordination and incentive structure, prevails in societies across the ages. Nevertheless, historical and institutional contexts condition adaptation and contingent arrangements. New contexts necessitate new forms of organizing. We know some forms work better than others in different contexts: sometimes it occurs by chance that a given organizational arrangement fits well the prevailing conditions; and sometimes a given form emerges, following many trials and errors, to achieve an acceptable and unintended order.

Emergence follows a now well-understood route. For instance, Plowman et al. (2007: 538), in their study of a radical transformation in a church, propose that, given a high level of organizational tension: (1) ‘emergence of small change and amplification into radical change [is encouraged …]’; (2) ‘resource availability accelerates a small change into radical change’; (3) ‘the use of language’ and ‘symbols accelerates a small change into radical change’; (4) ‘the interaction of amplifying actions accelerates a small change into radical change’; and (5) ‘the interaction of amplifying actions and contextual conditions accelerates small change into radical change’. In other words, a new order appears if forces at play exert tension on the system; a small change, if amplified, leads to a transformative process which, fuelled with new imported resources and positively reinforcing forces, leads to a new equilibrium. In the same vein, Chiles et al. (2004: 514), studying the emergence of Branson’s musical theatres, observe ‘four dynamic mechanisms of emergent self-organization: (1) spontaneous fluctuations that initiate a new social order; (2) autocatalytic feedback loops that amplify and reinforce these fluctuations; (3) coordinating mechanisms that help stabilize the emergent order; and (4) recombinations of preexisting resources that renew the social order, add variety, and fuel positive feedback processes’. Here again, consistent with Plowman et al.’s (2007) research, chance is at play. When chance triggers the process, similar dynamics appear: positive reinforcement to favour emergence; and stabilizing effects to prevent the new emergent order from dissolving into chaos. Chance, nevertheless, constantly challenges such equilibria. New emerging equilibria can also be reconstructed, subject to the enduring tension, as demonstrated in Lichtenstein et al.'s (2007: 244) research which shows that 'the positive-feedback process of self-organization, which occurs when the enactment of one activity generates characteristics that support the emergence of another activity, which supports the emergence of further activities, and so on'; and that 'the presence (completion) of each activity helps build a "scaffold" for emergence', thus 'providing a catalyst for further activities to be enacted'. McKelvey (1997; 1999) already alluded to such a successive scaffolding process in his emergent 'selectionist' contexts view. God's hand and chance are at play: order is there to be found; and chance helps in the search.

When complexity leads to simplicity and vice versa

System dimensionality matters. Depending on the dimension of a system, i.e. the number of variables involved, dynamics differ. On the one hand, high-dimensional (complex) systems are characterized by multiple levels and multiple variables interacting in a nonlinear fashion. This is the case with large organizations which, under the right conditions – energizing tension, an initial perturbation accompanied by positive reinforcement, and stabilizing forces – can be the receptacle of self-organizing activities. From complexity, simplicity, i.e. a self-organized order, emerges. On the other hand, low-dimensional (simple) systems are characterized by a few highly coupled variables in a dynamic and nonlinear fashion. This is the case with simpler and relatively contained processes such as innovation. From this relative simplicity, a complex dynamic equilibrium unfolds.

High-dimensional systems are the realm of self-organization and complex adaptive dynamics. Low-dimensional systems are the realm of chaos theory. In studying self-organization, we attempt to understand how complexity creates simplicity in the form of an emergent order, i.e. how a highly disordered state leads to an organized or ordered one. On the other hand, by applying chaos theory, we can attempt to understand how simplicity in the form of a low-dimensional, deterministic system creates apparent randomness. Apart from these differences, both dynamics involve tensions, energy exchange and dissipation, phase transition, stability, regularity, organized order, and deterministic randomness. They thus share similar features.

In our 1995 article on 'Chaos Theory and Organization' (Thietart and Forgues, 1995), we made several propositions based on chaos theory (see the left column in Table 2.1). After 15 years, we still believe these propositions to be a valid and relevant representation of low-dimensional system dynamics. Low-dimensional systems (1) are potentially chaotic; (2) evolve from one dynamic state to another following a discrete bifurcation process; (3) render forecasting impossible, especially at a global scale and in the long term; (4) are 'attracted' to an identifiable configuration, when in a chaotic state; (5) have a fractal form, when in a chaotic state; and, as a consequence, (6) are such that the taking of very similar actions in them leads to very different results.

We also present six new propositions for high-dimensional systems (see the right column in Table 2.1), which parallel our six original ones. Some propositions (Propositions 7, 8 and 11) are corroborated by empirical evidence (see Chiles et al., 2004; Lichtenstein et al., 2007; Plowman et al., 2007). Propositions 7 and 8 refer, first, to the self-organizing potential of complex organizations when they are subjected to counteracting forces; second, to the transition from one state of stability to a state of emergent order and then to a state of 'chaos', as a function of forces at play. Proposition 11 relates to the fractal form that organizations may adopt in time or in space. This hypothesized property, however, is only

Table 2.1 Propositions about the complex dynamics of systems

Low-dimensional systems *'Chaos theory'*	*High-dimensional systems* *'Self-organization'*
Proposition 1: Organizations are potentially chaotic	*Proposition 7*: Organizations are potentially self organizing
– 1a. the greater the number of counteracting forces in an organization, the higher the likelihood of encountering chaos	– 7a. the greater the number of counteracting forces, the higher the likelihood of encountering order
– 1b. the larger the number of forces with different periodic patterns, the higher the likelihood of encountering chaos	– 7b. the larger the number of forces (positive reinforcement and negative counterbalance), the higher the likelihood of encountering order
Proposition 2: Organizations move from one dynamic state to the other through a discrete bifurcation process	*Proposition 8*: Organizations move from one dynamic state to the other through a discrete transition process
– 2a. an organization will always be in one of the following states: stable equilibrium, periodic equilibrium, or chaos	– 8a. an organization will always be in one of the following states: stable equilibrium, emerging order, or disorder ('chaos')
– 2b. a progressive and continuous change of the relationships between two or more organizational variables leads an organization, in a discrete manner, from a stable to a chaotic state via an intermediary periodic behaviour	– 8b. subject to tension, an initial disturbance, if reinforced and kept under control, leads the organization from a state of stability to an unstable emerging order. – 8c. subject to tension, an initial disturbance, if reinforced, leads the organization from a state of stability to 'chaos' via an unstable intermediary emerging order.
Proposition 3: Forecasting is impossible, especially at a global scale in the long term	*Proposition 9*: Forecasting is impossible, especially at a global scale in the long term
– 3a. when in a chaotic state, *ceteris paribus*, the impact of a change has an unpredictable long term effect	– 9a. when in a self organizing state, *ceteris paribus*, the impact of a change has an unpredictable long term effect
– 3b. when in a chaotic state, *ceteris paribus,* the impact of an incremental change can be predicted in the very short term	– 9b. when in a self organizing state, *ceteris paribus*, the impact of an incremental change can be predicted in the very short term
Proposition 4: When in a chaotic state, organizations are 'attracted' to an identifiable configuration	*Proposition 10*: When self organizing, organizations evolve toward an identifiable emerging order
– 4a. when in a chaotic state, organizations are more likely to adopt a specific configuration than a deterministically 'random' pattern	– 10a. when self organizing, organizations are more likely to adopt a specific configuration than a 'random' pattern
– 4b. the greater the openness of an organization to its environment, the more likely is the 'attraction' by the organization to a given configuration	– 10b. the greater the openness of an organization to its environment, the more likely the organization evolves to a given configuration
Proposition 5: When in a chaotic state, organizations, generally, have a fractal form	*Proposition 11*: When in an emerging order state, organizations, generally, have a fractal form
– 5a. when in a chaotic state, similar structure patterns are found at the organizational unit, group and individual levels	– 11a. when in an emerging order state, similar structure patterns are found at the organizational unit, group and individual levels
– 5b. when in a chaotic state, similar process patterns are found at the organizational unit, group and individual levels	– 11b. when in an emerging order state, similar process patterns are found at the organizational unit, group and individual levels

(continued)

Table 2.1 (*Contd.*)

Low-dimensional systems *'Chaos theory'*	*High-dimensional systems* *'Self-organization'*
Proposition 6: Similar actions taken by organizations in a chaotic state will never lead to the same result.	*Proposition 12*: Similar actions taken by organizations in an emerging state will never lead to the same result
– 6a. when in a chaotic state, two identical actions taken by a same organization always lead to two different results	– 12a. when in an emerging state, two identical actions taken by a same organization always lead to two different results
– 6b. when in a chaotic state, the same action taken by two organizations never lead to the same result	– 12b. when in an emerging state, the same action taken by two organizations never lead to the same result

relevant for critically self-organized systems (Bak, 1996), where power-law phenomena prevail (Andriani and McKelvey, 2009). The other propositions – i.e., Proposition 9 on impossible forecasting, Proposition 10 on identifiable order, and Proposition 12 on replicability – extend the original propositions from low-dimensional to high-dimensional systems; and are based on the assumption that what holds true for low-dimensional systems also does so for high-dimensional ones.

As a synthesis, we propose that high-dimensional systems have a potential to self-organize. When subjected to tensions, an initial perturbation can subsequently be positively reinforced, thus opening the way to an emergent order. This emergent order however, if continuously positively reinforced, can then lead to 'chaos'. Thus, for this emergent order to be maintained it must be kept under control by dampening forces. It is therefore an unstable order. Further, in the case of power-law phenomena, scalable self-organizing dynamics may occur. In such situations, a fractal structure, i.e. self-similarity at different scales in time or space, is observed (see Andriani and McKelvey, in this volume, for further discussion of power-law phenomena).

CONCLUSION

When we launched our research programme on chaos theory back in 1992, we had a paucity of work in management to build upon. We therefore drew from physics, and eagerly read how finance scholars applied nonlinear mathematical tools to their datasets. Close to 20 years later, a wealth of contributions has transformed a burgeoning complexity science field into a vast and diverse set of ideas, concepts, methods, and research themes. Among these, we still find metaphorical applications of complexity science to organizations which are less rigorous than we would like. However, such loose applications of complexity science are much less prevalent now than before.

As chapters in this Handbook show, the field is now comprised of an impressive array of high quality research. Better grounded works dominate in such areas as entrepreneurship, leadership, change, innovation, strategy process and competitive dynamics. At the same time, complexity science-inspired methods have also become well established. The literature now contains a large number of first-rate simulation-based research projects, event studies, analyses informed by techniques from econometrics, and qualitative studies of dynamic phenomenon, all of which establish 'firm foundations' (Maguire and McKelvey, 1999) for further research advances. But richness in themes and methods in the application of complexity science to organization has its drawbacks: it can be intimidating to newcomers; it often entails a steep learning curve; and, until recently, it lacked structure.

We believe that the field is still in the emerging stage of order creation. There is certainly evidence of positive reinforcement with the increasing acceptance of complexity science as a legitimate approach to the study of organization. However, we also believe that the necessary stabilizing forces, without which complexity science as applied to organization could become a very messy field, are missing. So this Handbook represents a much-needed contribution to efforts to organize the field. We are on the right path.

But to where? In the future, more theoretical and empirical research needs to be done to consolidate the foundations on which complexity science as applied to organization is being built. Three areas seem particularly promising and challenging. The first area is conceptual: we argue that scholars must seek to develop a consensus around and stabilize convergent definitions. Second, we argue that process research that draws on econometric tools, as in the field of finance, in order to disentangle and shed light on the dynamics behind order creation could be an excellent addition to the qualitative work which has successfully been undertaken in recent years. Third, we argue that multi-level research into process dynamics also offers a promising new direction for investigation. As a scholarly community, we must endeavour to meet these new challenges and move forward along the path we are creating.

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3

Emergence in Complex Systems

Jeffrey Goldstein

INTRODUCTION

This chapter explores the phenomena of emergence in complex systems in order to review and comment on organizational research applications of the idea. First, six prototypes of emergent phenomena in complex systems are presented, with an eye towards delineating a set of common characteristics possessed by emergent phenomena across a wide variety of different types of complex systems including organizational systems. Next, the chapter reviews recent utilizations of the idea of emergence in organizational studies. The 'dissipative structures' model underlying much of this research is then explicated emphasizing the strong coupling between so-called self-organizing processes and the production of emergent phenomena. A new approach to emergence is then developed by first unpacking the various 'folklore' and conceptual snares that have become associated with emergence. This new model of emergence, based on the formalism of self-transcending constructions, is unfolded out of several suggestions offered about emergence by various researchers and theorists during the history of complexity science. The construct of self-transcending constructions is elaborated towards how it remedies several of the insufficiencies of the self-organizational approach. Finally, the chapter concludes with remarks on how emergence can aid in research into organizational adaptability.

SIX PROTOTYPES OF EMERGENT PHENOMENA IN COMPLEX SYSTEMS

Research into the phenomena of emergence in complex systems has yielded a set of at least six prototypical conceptualizations, each with its characteristic theoretical underpinnings (in italics):

1. Phase transitions, 'quantum protectorates' and similar critical phenomena in condensed matter physics (Anderson, 1972; Laughlin, 2005; Batterman, 2009): *symmetry-breaking; order parameters: renormalization group: universality*; and *criticalization*.
2. Self-organizing physical systems (Haken, 1981; Allen and McGlade, 1987; Nicolis and Prigogine, 1989; Haken, 2008), *dissipative structures: far-from-equilibrium conditions; order parameters*; *'enslaved' variables*; and *self-organization*.

3 Mathematical emergence in dynamical systems (May, 1976; Cohen and Stewart, 1994; Martelli, 1999; Scott, 2007): *nonlinearity; phase space; bifurcations; attractors*; and *chaos*.
4 Computational emergence (Langton, 1986, 1996; Adami, 1998; Crutchfield, 1993, 1994; Holland, 1994, 1998; Marinaro and Tagiaferri, 2002; Griffeath and Moore, 2003): *artificial life; neural nets; Game of Life*; and *computational mechanics*.
5 Social emergence including virtual social networks of the internet (Addis, 1975; Johnson, 2002; Sawyers, 2005): *collectivity; social networks; artificial societies*; and *cooperation*.
6 Biological emergence (Goodwin and Sole, 2000; Reid, 2007; McShea, 2000): *new speciation; morphogenesis; symbiogenesis*; and *hierarchical constructions*.

Although emergent phenomena cover a wide range of diverse disciplines and various typologies have been suggested for them, common characteristics include: radically novel macro-level entities and properties with respect to a micro-level substrate: ostensiveness in the sense of unpredictability and non-deducibility; integrated coordination characterizing the macro-level; and dynamical in the sense of coming to be over time (Goldstein, 1999). The Nobel laureate Laughlin (2005) holds we are now leaving the Age of Reductionism and entering the Age of Emergence.

BACKGROUND AND HISTORY

The modern sense of the term 'emergent' (and by extension 'emergence') was coined in 1875 by the philosopher Lewes (1875: 368–369) when discussing the changing nature of causality:

> ... although each effect is the *resultant* of its components, we cannot always trace the steps of the process, so as to see in the product the mode of operation of each factor. In the latter case, I propose to call the effect an *emergent*. It arises out of the combined agencies, but in a form which does not display the agents in action.

It took several decades for Lewes' definition to influence the movement known as Emergent Evolutionism (Blitz, 1992; Stephan, 1999; Goldstein, forthcoming) promulgated by prominent philosophers and scientists such as Samuel Alexander, Conwy Lloyd Morgan, C.D. Broad, Roy Wood Sellars, W. Wheeler, Alfred North Whitehead, Arthur Lovejoy, and George Herbert Mead. The idea of emergence was proposed as a supplement and thereby correction to an overly mechanistic and incrementalist view of evolution in Darwin's theory. It was held that emergence could steer between mechanism and vitalism on the other.

Emergent Evolutionism was just the *proto*-phase of emergentist thought, succeeded by a *mid-phase* lasting from approximately 1940 to 1975 and the current *neo*-emergentist period accompanying the rise of complexity theory. During the mid-phase period, the concept of emergence was influential in the philosophy of science, the spread of Whitehead's process philosophy and process theology, theoretical biology, and the nascent field of neuroscience (Goldstein, forthcoming).

THE USE OF THE CONSTRUCT OF EMERGENCE IN ORGANIZATIONAL RESEARCH

Emergence has surfaced as an important construct in studies of organizational dynamics and leadership in particular (Romanelli, 1991; Gartner, 1993; Katz, 1993; Goldstein, 1997, 1999, 2006; MacIntosh and MacLean, 1999; Marion and Uhl-Bien, 2001; Guastello, 2002; Chiles et al., 2004; McKelvey, 2007; McKelvey and Lichtenstein, 2007; Lichtenstein and Plowman, forthcoming; Plowman and Duchon, 2007, 2008; Plowman, et al., 2007a,b; Schwandt, 2007). Lichtenstein et al. (2006) have begun quantizing emergence via time series analysis as well as a multi-level longitudinal content analysis of organizational texts.

In general these appeals to the construct of emergence are suggesting an alternative way that organizational structures, strategies, and practices, as well as leadership and follower roles can arise without being due to an imposition from command/control hierarchies. Appealing to emergence, accordingly, explains varied aspects of organizational dynamics through emphasizing spontaneous innovations which emerge out of interactions within social networks of persons and between persons and technologies. Typically, these innovations in organizational functioning are understood as the emergence of collectivities at the macro-level out of connectivities at the micro-level. Moreover, because these innovations are not the result of imposition, it is believed they are more likely to exhibit creative solutions, are more likely to evoke employee commitment, and consequently are more likely to empower rather than disempower employee contributions.

One of the dominant theoretical underpinnings shared by many of these researchers employing the idea of emergence is a 'dissipative structures' model derived predominantly from the approaches found in the first three prototypes of emergent phenomena listed above, particularly that of number two, namely, the work on self-organizing physical systems pioneered by Prigogine and Haken and, to a lesser extent, the nonlinear dynamical systems prototype of number one, the latter the main perspective, for example, taken by Guastello (2002).

A salient example of an organizational application of emergence following the dissipative structures model is the study conducted by Chiles et al. (2004) on the sundry 'organizational collectives' involving country music that have sprang up around the town of Branson, Missouri which have been attracting over 6 million visitors annually. These collectives have arisen 'spontaneously' over the years mostly without the intervention of some centralized hierarchical guiding facility.

Combining the research of Chiles et al. (2004) with some of the other examples of organizational uses of the idea of emergence, such as found in McKelvey and Lichtenstein (2007) and Lichtenstein and Plowman (forthcoming), this 'dissipative structures' model can be said to possess at least four elements or stages of emergence:

1. A period of disequilibrium in which spontaneous fluctuations emerge forming the seeds of new emergent order;
2. Positive feedbacks which amplify the fluctuations of #1;
3. Recombinations and new correlations of existing resources, capabilities, symbols, language, and work patterns;
4. Coordinating mechanisms that stabilize the new emergent order.

From within the purview of this model, for example, Chiles et al. (2004) understand emergence as involving a 'self-organizing logic' composed of a set of 'hodge podge configurations' neither 'planned', controlled,' nor 'created' through 'human design' (p. 510).

Most of the organizational appliers of emergence hold that these self-organizing processes operate in a 'bottom-up' fashion which means they are considered to be more prone to occur when command and control mechanisms are relaxed or dismantled. As a result, in an important sense, such a perspective has tended to suggest a passive or *laissez-faire* leadership style. Partly in response to the latter implication but also to both take into consideration what actual research into emergence in complex systems actually reveals, e.g. in biological emergence and in artificial life as well as its mathematical formalisms, recently Goldstein (2001, 2002, 2004, 2006, forthcoming) has suggested supplementing the dissipative structures/self-organizational model of emergence with one that focuses more on the constraining and constructional operations discernible in nearly all complexity research into emergence, an approach that will be further expounded below.

'FOLKLORE' SURROUNDING EMERGENCE

The notion of emergence has through all its three periods provoked responses and criticism from within the philosophy of science (see Goldstein, 2000; Wimsatt, 2007; Bedau and Humphries, 2008). This is not surprising since, although the idea of emergence offers many conceptual benefits, it doesn't come without enigmatic and elusive threads involving sundry bits of 'folklore' which have grown up around the idea as well as varied philosophical snares associated with it. 'Folklore' is being used intentionally to indicate those connotations of the idea which are derived from popular *mis*-interpretations of research findings. Since to not address these troublesome issues would only serve to forestall the usefulness of organizational applications of the idea of emergence, this 'folklore' and these conceptual snares must be addressed.

Folklore #1: Complexity arises suddenly from simplicity

The first bit of 'folklore' concerns the claim that the complexity exhibited in emergent phenomena arises directly, spontaneously, and suddenly out of simpler or even random dynamics. Such an interpretation was often touted in the early days of chaos theory when technical 'chaos' was shown mathematically to emerge out of deceptively simple mathematical operations (see May, 1976). However, just because an outcome is startlingly novel with respect to its antecedents, doesn't necessarily mean there are not a host of intermediate means by which the novelty ensues (Goldstein, 1996). A close inspection of the logistic equation, for example, which has become something of an emblem of chaos theory, demonstrates various complex mathematical operations taking place such as: criticalization of parameters; bifurcations; iterative and recursive operations; and so on. There are also multifarious sources of nascent order and sundry 'complexifying' operations taking place in the emergence of novel order in the physical laboratory. This finding is analogous to Turing's (1952) remarks: 'Most of an organism most of the time is developing from one pattern to another not from homogeneity into a pattern' (quoted in Kelso, 1995: 3).

Folklore #2: 'Order for free'

The second representative of 'folklore' is Kauffman's (1995) influential concept of 'order for free' in how he has understood the implications of self-organization. One of the reasons Kauffman postulated the order observed in his networks was 'for free' had to do with *random* assignation of rules by which his networks operate which would seem to imply there was no pre-set design at work, hence the emergent order was 'for free'. Yet Kauffman (1995) admitted, '… if the network has more than $K = 2$ inputs per light bulb, then certain *biases* in the Boolean rules, captured by the P parameter, *can be adjusted* to ensure order' (103; emphases added). Although the identification of this bias had to wait until after the run of a simulation, the important point is that emergent order only ensued when the biased rules were operative. But these biases were *built-into* the rules so that the order which emerged was *constructed* to do so and hence not 'free' at all.

A focus on 'order for free' tends to neglect the indispensable role of the 'containers' and other constraining and constructional operations involved in emergence, e.g., Berge, et al. (1984) found that in the Bénard convection, a typical example of the 'dissipative structure' model of emergence, the distance separating two neighboring currents is on the order of the vertical height of the container. Similarly, the number of convection rolls can be curtailed by reducing the ratio of the horizontal dimension to the vertical height of the container. Weiss (1987), in turn, found that instabilities in the thermal boundaries of liquid systems similar to the Bénard system lead to more complicated kinds of convection. These 'costs' are overlooked when emergent order is thought of as 'for free'.

In terms of organizational researchers advocating the use of the construct of emergence, an enthusiasm for 'order for free' shows up in the above-mentioned claim that emergence is more likely to take place in the face of a relaxation of or dismantling of the normal command and control hierarchy. Moreover, holding to the presumption that emergent order is 'for free' not only has the unfortunate effect of neglecting very important determining conditions of emergent order, it also neglects the fact that emerging order may not be beneficial at all. For instance, in many respects, cancer cells are emergent order and yet they are clearly not advantageous to the patient.

Folklore #3: The 'edge of chaos'

Too many proponents have mistakenly argued that emergence is more likely to take in what is believed to be a particularly 'pregnant' zone during the evolution of a complex system termed the 'edge of chaos'. The notion originated when the artificial life researchers Langton (1990) and Packard (1984, 1988) claimed to have shown in computer simulation that there was a special verge in complex systems which they called the 'edge of chaos' where emergent phenomena were supposed to more likely manifest themselves. Langton contended that as his statistic λ increased, the complexity of the dynamics would increase as the system moved towards a region where emergence was more likely. Packard, in turn, used a genetic algorithm to evolve cellular automata to perform complex computations, contending, like Langton, that he had identified a special 'edge of chaos' where such a capability was at its prime. Packard interpreted his findings to imply that when complex computation (read: 'complex emergence') is required, evolution selects rules that lead to a cognate 'edge of chaos'.

This notion was taken up by Kauffman (1995) who made it a centerpiece in his speculations on the theory of evolution:

> … on many fronts, life evolves toward a regime that is poised between order and chaos … It is a very attractive hypothesis that natural selection achieves genetic regulatory networks that lie near the edge of chaos … life exists at the edge of chaos … The best exploration of an evolutionary space occurs at a kind of phase transition between order and disorder … as if by an invisible hand, the system may tune itself to the poised edge of chaos … (pp. 25–28).

Indeed, Kauffman has repeatedly argued that biological organisms possess an innate propensity to evolve to such a state because of its adaptive potential.

Even though the 'edge of chaos' apparently offers a metaphor tempting in its usefulness, the original computational experiments on which the idea was founded by Langton and Packard were later discovered to be faulty by other artificial life researchers, namely, Mitchell et al. (1999); Mitchell et al. (1993). Replicating the work of Langton and Packard, they found just the opposite: those cellular automata rules with a capacity for producing complex emergent phenomena were in fact not found in some transitional 'edge of chaos' region at all. These researchers exhumed the most problematic aspect of Langton's work in his not having correlated λ with an independent measure of computation, an inadequacy which Packard did try to remedy but without much avail. Mitchell et al. (1999) discovered, by contrast, from their own computational experiments,

> there is no evidence for a generic relationship between λ and computational ability in CA and no evidence that an evolutionary process with computational capability as a fitness goal will preferentially select CAs at a special λ region. (p. 11)

Instead, they found both that a given run was organized around the patterns that appeared earliest and that the supposed 'phase transitional' regime in which symmetry was broken was simply not the best realm for computational efficacy. Later, Crutchfield, working with Hanson (1997), discovered that the kind of computational capability associated with emergent phenomena was more likely to take place in the dynamical region characterized as the 'chaotic' rather than the 'edge of chaos', but that this can be difficult to observe due to the 'filters' used in exploring the chaotic regime. Although Kauffman has broadened the scope of his 'edge of chaos' to suggest some kind of criticalization in general, the pioneer in the study of self-organized criticality, Bak (1996), has found no evidence to substantiate Kauffman's claim that evolution has an impetus to evolve towards criticalization as a particularly well-suited condition for evolutionary 'experiments'.

Folklore #4: Emergence only takes place through self-organization

The close association between emergence and self-organization goes back at least to the schools of Prigogine and Haken both of which put the onus on how the emergence of new order takes place onto self-organizing processes. In this model of emergence, the 'self' of 'self-organizing' connotes such properties as 'innate', 'unplanned', 'spontaneous', and susceptible to taking place in 'leaderless' situations. These connotations match the characterization, on the part of Chiles et al. (2004), of the emergence music theaters around Branson, Missouri as guided by a 'self-organizing logic' neither 'planned', 'controlled', nor 'created' through 'human design'.

However, a close inspection of how emergent order does come about in each instance when it does shows that a lot more than self-organizing processes are necessary. Although one might have supposed that the 'organizing' part of 'self-organizing' would draw attention to structure building, most appeals to self-organization in fact tend to neglect structuring operations. Yet, if, as McKelvey (2001) avows, complexity in organizations is about *order creation*, then a main issue should be how emergent order is *constructed*. Although self-organizing processes play a role in emergence, a wider and more general conceptualization of emergent order generation is needed that can include the varied and special types of constructional operations involved in the emergence of new order, again an issue which will be gone into below.

As a matter of historical fact, the notion of construction as such was intimately tied into emergence right at the beginning of contemporary *neo*-emergentist research when Anderson (1972), a winner of the Nobel Prize in physics, offered his 'Constructionist Hypothesis' as a response to arch reductionism rampant among particle physicists. This hypothesis proposed that although it might be possible to reduce nature to certain simple, fundamental laws, this did not then entail a similar ability for re-constructing the universe from these simple laws since each new level of complexity involved the emergence of entirely new properties and laws not appearing at the lower levels. That is, each new level of complexity would exhibit the construction of new structures with new properties that transcend lower level characteristics and dynamics.

Indeed, supposed exemplars of emergent phenomena in the laboratory require strenuous *non*-self-organizational processes, a case in point being the coherence of lasers which Haken (2008) has put forward as the prototype of emergence and self-organization. For laser light to be generated, however, involves constraining and constructional operations that don't fit into the self-organizational conceptual box (see Strogatz, 2003).

CONCEPTUAL SNARES IN UTILIZING THE IDEA OF EMERGENCE

As stated above, besides the sundry folklore surrounding the idea of emergence, there are also varied conceptual snares involved with issues in the philosophy of science (Goldstein, 2000; Wimsatt, 2007; Bedau and Humphries, 2008) which need to be addressed so that the use of the idea of emergence can avoid the problematic aspects of these issues and thereby advantageously used in theory and research. One issue concerns the specific role of emergence in scientific explanations. A crucial reason for appealing to emergence in the first place is when the dynamics of a complex system lends itself to a more thorough understanding through attention to the across-system *organization* at a macro-level and not just the micro-level constituents alone (Bechtel and Richardson, 1993). This appeal usually arises when the macro-level patterns, structures and properties of the higher level organization appear intractable to prediction and deduction from, as well as reduction to, the lower level of parts. Turning to emergence in appealing to the macro-level organization does not so much explain the system's dynamics as it provides a pointer to where explanations would need to lie, emergence then serving more as an *indexical* marker directing the research agenda to the dynamics of the emergent level as well as those operations having the potency to bring about the properties observed on the emergent level.

This implies that the role of emergence in explanatory strategies requires both emergentist *and* reductionist inquiry (Wimsatt, 2007). Clark (1996), in fact, has asserted that to emphasize the contrast between emergentist and reductionistic explanations invites the misleading claim that accounts utilizing the idea of emergence have nothing to say about how emergent order arises.

Another issue concerns the ontological status of the entities, patterns, and properties of the emergent level. This is related to the claim that the emergentist status of the higher level is merely provisional, i.e. only useful until the advent of a more thorough micro-level explanation. In dealing with this issue, Crutchfield (1993) has pointed out that the emergent patterns detected by scientists are often assumed to be there through assumptions implicit in the statistics used in detection. To correct this subjective bias, Crutchfield proposes defining emergence according to its 'intrinsic computational capacity'. Hence, attention must be given to how much subjective bias and preconceived assumptions are entering the recognition of emergent phenomena.

Another puzzling feature involves the nature of the *coherence* observed in emergent phenomena. For instance, the coherence of 'dissipative structures' is often described in very stringent terms: an across-system correlation which 'overpowers' local or lower level forces (Nicolis, 1989), or as 'enslavement' (Haken, 1981). It is questionable whether such a strenuously rigid definition of emergent coherence is appropriate for 'organized collectivities', 'emergent networks', and so on. It is exactly this kind *of inflexible* order that the complexity-oriented economist Page (2007) challenges with his notion of the powerful role of differences in a complex system, i.e. heterogeneous elements allowed to express their individual differences while, at the same, time operating as a unity.

Still another conceptual snare lies in wait when it comes to the idea of a novel emergent *level*. Wimsatt (2007) describes the notion of a level in a complex system as that which houses entities with comparable size, rates of change, patterns, and dynamical properties. In other words, an emergent level consists of entities and their relations that hang together more strongly with one another on the same level than they do with other units and relations on other levels. Although they are often conflated, an emergent level is different than the notion of scale *per se* (Goldstein, 2002). This distinction is necessary to keep in mind in the face of research involved with scaling dynamics in complex systems, e.g. the finding of power law signatures in social network dynamics (Barabási, 2002). Rather than being self-similar to levels at different scales, emergent levels can be taken as implying a type of scale *variance* or what Wolpert and Macready (2000) refer to as *self-dissimilarity* at different levels. Taking the latter into consideration puts emergence in greater accord with Anderson's (1972) emergentist Constructionist Hypothesis mentioned above.

Furthermore, emergent levels are constituted by thick interactions with other levels in the sense of Hofstadter's (1979) 'tangled hierarchies' or 'strange loops' and Wimsatt's (2007) notion of 'causal thickets' which stress the difficulty of localizing unambiguously an entity on any one level. This is also why it is often the case that the interplay between the level of parts and that of organization is what yields the highest explanatory payoff (Lewin, 1992). The study of emergence in complex systems is a much messier matter than either presuming the self-similarity of scale invariance or holding that emergent levels are crisply distinct with each other. This also implies that in organizational applications of the construct of emergence there will be many opportunities for getting confused about what is happening on what level.

Another pervasive conceptual issue concerns how emergence has been thought to involve some kind of breach in causality. This issue began way back in the history of emergentist thought when the idea of emergence was used as a bulwark against overly mechanistic explanatory strategies. Vestiges of this view of emergence can be found, for example, in Stacey's (1996) recent contention:

> Causal links between specific actions and specific organisational outcomes over the long term disappear in the complexity of the interaction between people in an organisation, and between them and people in other organisations that constitute the environment. (p. 187)

Although Stacey was not averring that complex systems are *a*causal but rather that their causal links can be obscured, such a caution is frequently overlooked. In a phrase, complex systems demand complex causality.

An issue closely related to that of causality has to do with the purported unpredictability customarily assigned as a defining characteristic of emergent phenomena. A significant source of this unpredictability comes from the way that emergence can incorporate randomness into construction of the new emergent level. As Allen and McGlade (1987) stated, it is often the random departures of systems from norm-seeking, average behavior which are decisive for their adaptive capability. Nicolis (1989) put it this way: a system under the influence of random occurrences due to an unpredictable environment may develop temporary structures or processes suitable for novel occasions as they may arise. Furthermore, because self-organizing processes are supposed to happen on their own spontaneously and are said to be neither directed, conditioned, nor guided, it is believed they cannot be known ahead of time.

However, there are crucial limitations on just how unpredictable emergence is. Indeed, even research into 'dissipative structures' shows they are indeed predictable to the extent that given the right container, and the right liquid, and the right process of heating, the Bénard convection cells will emerge, and their patterns will be quite similar to those observed in previous experiments. Furthermore, the only thing totally unpredictable in the Bénard system is the directionality of movement of each hexagonal convection cell since this directionality hinges on which specific random currents become amplified (see Nicolis and Prigogine, 1989). Predictability also shows up in the Game of Life (Poundstone, 1985), an exemplar of the computational emergence of artificial life, where, for example, the presence of two emergent patterns called 't-tetraminos' in close proximity to one another can be used to predict the later emergence of another pattern, the 'pentadecathelon'. At first, this predictability was unknown so the 'pentadecathelon' was presumed to be an unpredictable emergent, but now that a correlation has been established between the 't-tetramino' and the 'pentadecathelon', the latter has become much more predictable, a progress in prediction that is continuing as more and more outcomes of the Game of Life are catalogued and studied (see Griffeath and Moore, 2003). As more is put into taxonomies and typologies of emergent phenomena, such classification schemes will no doubt aid in the discovery of repeating patterns and thereby greater predictability.

THE SELF-TRANSCENDING CONSTRUCTION OF EMERGENT ORDER

To adequately address the problematic aspects of both the folklore and conceptual snares associated with the idea of emergence a well as the imputation that emergence requires a passive leadership style, a new model of emergence has been offered by Goldstein (1996, 1997, 2001, 2002, 2003, 2004, 2006). An unfortunate consequence stemming from an over-emphasis on self-organizing processes as the key to emergence has been the driving of a conceptual wedge between the supposedly spontaneous, inner-directed processes of self-organization and those otherwise constructional in nature. In Goldstein's revised model, this wedge is removed with the result that self-organizing process will still play an important role but only as taking place alongside the more overtly structuring operations. This wider model of emergence is termed 'self-transcending constructions' (stcs) which focuses on how pre-existing order in a system undergoes sundry 'complexifying' operations (Ehresmann and Vanbremeersch, 2007) as it is transformed into radically novel emergent order. The 'self-' and 'transcendence' of 'self-transcending' refer to how emergent order *arises out of* yet *transcends* the lower level and antecedent substrate. The idea of self-transcendence includes four fundamental requirements for understanding emergence: building blocks; constructional operations utilizing the building blocks; constraining and containing factors; and a simultaneous transcendence of building blocks.

Formalizing emergence as self-transcending constructions

In order to sketch out the outline of a formalism of stcs, it is helpful to turn to the great French mathematician Thom's (1998) description of what's involved in a formalism: intuitions about a subject matter are organized as a morphology $\boldsymbol{T}$ so that, given a formal set of symbols and rules generating a formal system $\boldsymbol{S}$, an isomorphism between $\boldsymbol{S}$ and $\boldsymbol{T}$, $\boldsymbol{S} \leftrightarrow \boldsymbol{T}$, is established which attaches a 'meaning' to any symbol $\boldsymbol{s}$ belonging to $\boldsymbol{S}$. Although the intention of a formalism is that $\boldsymbol{T}$ will be fully covered by $\boldsymbol{S}$, it's more likely that only a 'local zone' of $\boldsymbol{S}$, $\boldsymbol{Z_S}$, in the morphology $\boldsymbol{T}$ is complete so that at the boundary of $\boldsymbol{Z_S}$, the correspondence of $\boldsymbol{S}$ and $\boldsymbol{Z_S}$ breaks down which then prohibits an extension beyond $\boldsymbol{Z_S}$ of the isomorphism $\boldsymbol{S} \leftrightarrow \mathrm{T}$. Applying Thom's scheme to formalizing emergence as stcs, the $\boldsymbol{S}$ would first need to include the various extant formalisms that have been developed to study emergence in its various guises including:

- nonlinear dynamical systems theory ('nds') with the formalisms of difference equations, coupled differential equations, phase space, attractors, and bifurcations;
- the constructs of symmetry-breaking found in solid state physics where emergence has been associated with phase transitions;
- the constructs used by the Prigogine School to formalize 'dissipative structures', e.g. thermodynamics as well as dynamical systems;
- the constructs used by the Haken School to formalize self-organizing systems such as order parameters and 'enslavement' of variables;
- the mathematical formalisms found in the artificial life variety of computation emergence;

- the high level abstract mathematical formalisms of emergence found, e.g., in the set theoretical, mathematical logic, and category theoretical approaches of Ehresmann and Vanbremeersch (2007) and Hofstadter (1979).

It must also be recognized that self-transcending constructions must possess a unique potency in order to capture the radical novelty generating characteristic of emergence – more specifically, the constructional operations must be *special* types of constructions if emergence is to live up to its claim of amounting to something transcending ordinary change. In other words, a formalism for stcs must show a transcending of the very same lower level antecedent conditions out of which the higher emergent level is constructed. The reader is referred to Goldstein (2001, 2002, 2004, 2006, forthcoming) where the radical novelty generating aspect of the new model for emergence is expressed in terms of a mathematical logical definition adapted from the work of Simmons (2008).

'Construction' in this sense doesn't necessarily entail an *external* construct*or* since novel order can arise out of the interaction of elements which are already ordered to some nascent extent. An example is how the internal organization of a cell is constructed out of a complex interaction of self-regulatory feedback loops, protein folding, multi-molecular modularization, and other spatial and temporal constraining operations in tandem with genetic information (see Moss, 2003).

To better appreciate what is involved with the proposed new formalism for emergence, it is helpful to briefly describe several of the approaches that have been inspirational for it. The first intimation of this formalism of stcs was Reiser's (1935: p. 63) description of emergent wholes using an analogy from transfinite set theory:

> Just as assertions about the properties of finite classes cannot be made to apply to transfinite aggregates, so in a similar way, the peculiar non-additive properties of an emergent whole (gestalt) cannot be predicated of the constituent parts. (p. 63)

A crucial step in transfinite set theory, as developed by Cantor in the latter quarter of the nineteenth century (Tiles, 1989), was later disparagingly described as absurd since it relied on an impossible 'self-transcending construction' by Kaufman (1978), an eminent Austrian philosopher of mathematics. Yet, it was just this same expression that motivated the naming of the formalism for emergence offered here since the phrase 'self-transcending construction' fit very aptly the way emergent phenomena are produced out of, yet transcend lower level components.

Stcs played an indirect but indispensable role in later approaches to emergence, via the theorems in mathematical logic formulated in 1931 by Gödel (1962) and in 1937 by Turing (1937) which relied on the same stc as Cantor used in his proof of transfinite sets. Indeed, the same self-transcending constructional argument is also at the basis of the complexity metric called *logical depth* devised by Bennett (1988), a complexity oriented physicist and computer scientist. Another argument from Gödel/Turing found its way in Cohen's and Stewart's (1994), 'Existence Theorem for Emergence' which proposed that emergent phenomena could not be expressed except in intractably long deductive chains emanating from their lower level or antecedent conditions. Along the same vein, this self-transcending constructional model showed up in the work of von Neumann (von Neumann and Burks, 1966), on self-reproducing automata which has served as a major influence of the computational emergence of artificial life. The links between the emergence found in artificial life and the formalism of stc is also exhibited in several sources: the 'object construction' theory put forward by Fontana and Buss (1996) as an improvement over the dynamical system conceptualizations of phase space and attractors; and Holland's (1994, 1998) computational model of emergence based on his recursive scheme of 'constrained generating procedures' (cgps) which can be considered a type of rudimentary self-transcending construction.

In general, whereas a model based on self-organization alone would tend to emphasize how emergent order happens on its own when controlling mechanisms are relaxed, a model of emergence based on self-transcending constructions instead emphasizes a host of structuring operations. This in turn indicates that leadership in emergent systems would be better understood according to the constructional roles of expediting constructional activities, linking people and projects, shaping, and other constructional ways of facilitating the emergence of novel structures.

CONCLUSION: THE FUTURE OF EMERGENCE IN ORGANIZATIONAL RESEARCH

When it comes to the adaptability of an organization to a changing environment, a random search among new possibilities of organizational functioning is not the most effective means toward adaptation to its environment (Kauffman, 1995). Indeed, when a search is merely random with no clues about upward trends, the only way to find the highest pinnacle is to search the whole space. This can be seen in biological as well as technological evolution since they both consist of processes that attempt to optimize systems riddled with conflicting constraints (Kauffman and Macready, 1995).

Turning to emergence offers itself as a way to rethink organizational adaptability, particularly when emergence is understood as incorporating 'self-organizational logic' but also utilizing various constructional and constraining operations as proposed in the model of self-transcending constructions. Indeed, Maguire (1999) has suggested that the search for improvements in adaptability amounts to a *design* problem since it is a matter of understanding diverse options among various combinations of organizational processes to construct a strategy. The idea of 'design' is counter, though, to the above-mentioned cleaving of self-organization as a natural, spontaneous occurrence from construction, artifice and design.

What's necessary for future research is how organizational emergence can be guided toward granting greater adaptability to organizations. Since randomness alone doesn't supply the answer, there will be a need for assessing the varied constructional approaches that are possible. The self-transcending constructional approach to emergence instead calls on organizational players to play a more active role than the passive one implicated in a purely self-organizational approach. Research is now under way and will accelerate in order to determine in more detail what exactly is involved in this more active, constructional role.

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4

Constructing and Appreciating Complexity

Steve Maguire

INTRODUCTION

The emergence of a science of complexity that increasingly is applied by organizational researchers and practitioners to management motivates this Handbook. But what, precisely, is complexity? This chapter explores this deceptively simple question with an emphasis on the implications of the epistemological challenges of complexity. These stem from issues of representation, prediction and interpretation; and are particularly relevant for social scientists. The chapter begins by briefly describing the various natural science research strands from which contemporary complexity science has emerged, as well as the features which characterize complex systems. It then elaborates and explores the epistemological issues associated with defining and measuring complexity, using Gell-Mann's (1994, 1995, 2002) seductive notion of 'effective complexity' to illustrate how agents in and observers of a complex system are each implicated in constructing complexity. The role of competing interpretations in constituting complexity is discussed, as well as that of different strategies for engaging with complexity. The chapter concludes by underlining the importance of appreciating complexity and its implications.

CONSTRUCTING COMPLEXITY

Emergence of complexity science

For the past three decades, complex systems have received increased attention from a diverse set of scientific disciplines, and from this has emerged a broad interdisciplinary science of complexity (see Anderson et al., 1988; Nicolis and Prigogine, 1989; Lewin, 1992; Waldrop, 1992; Kauffman, 1993; Casti, 1994; Mainzer, 1994; Bar-Yam, 1997). Two broad scientific programmes, increasingly overlapping, anchor the development of complexity science (McKelvey, 2004). A European School of complexity (see Table 4.1) draws from the physical sciences and emphasizes far-from-equilibrium conditions to explore 'self-organization', which is conceptualized as the emergence of order from disorder due to small perturbations, i.e. 'order through fluctuations' (Nicolis and Prigogine, 1977) or 'order out of chaos' (Prigogine and

Stengers, 1984); while, in parallel with this, 'synergetics' (Haken, 1977) was developed from work on lasers. For example, merely heating a pot of water from underneath can result in order and organization as geometric patterns of hotter and colder water appear (Bénard, 1901). Prigogine (1955) termed such order a 'dissipative structure' because it maintains itself by dissipating the applied energy differential; absent a continued flow of energy, entropic processes would lead the system to equilibrate without order or organization, in accordance with the Second Law of Thermodynamics – i.e. water temperature would be unpatterned and homogeneous throughout. Using mathematical models, and emphasizing critical values at which phase transitions from disorder to order occur (and vice versa), research in this tradition focuses on how unorganized entities in a given system seemingly organize themselves into coordinated structures that sustain or reproduce themselves when subjected to an externally imposed flow of energy. This work was extended beyond consideration of stability *within* a given system to the question of the structural stability *of* a system (Allen, 1976) and the possibility of new entities and processes emerging, which linked these ideas to the questions of biological, ecological and social evolution.

In contrast, the North American School (see Table 4.1) draws from the life sciences and makes extensive use of computational approaches. Researchers in this tradition use agent-based models to simulate the emergence of order among large numbers of coevolving entities or 'agents' in the form of patterns of evolved agent attributes and rules, as well as hierarchical structures which represent a nexus of both upward and downward causality. It is theorized that such systems of agents evolve spontaneously to a state of 'self-organized criticality' (Bak, 1996) at which the size and frequency of restructuring events among agents is related by an inverse power law.

A full explanation of emergent order requires reference to concepts from both Schools: the European School emphasizes system-environment processes; whereas the North American School emphasizes intra-system processes. McKelvey (2001), using thermodynamic theory and building on Cramer (1993), relates the two approaches by drawing attention to a system's first and second 'critical values', which demark phase transitions and thus define lower and upper bounds of a region which can give rise to what is termed 'complexity'. This occurs when system-level phenomena are characterized by patterns in time and in the system's movement through its state space – i.e. the space of possible values of variables of interest to observers and used to characterize the system – that are neither static nor randomly changing. Rather, these patterns are difficult to describe, to re-create, and to predict due to their intricacy and the coupling of agent-level and system-level behaviors. Broad patterns of behavior may be anticipatable, but an individual agent's and the system's specific paths through a space of possible states are difficult if not impossible to predict.

Further, because systems capable of giving rise to complexity are open ones at far-from-equilibrium conditions in which the ongoing interaction of parts is sustained through the import of information and energy-matter from the system's environment, delimiting the boundary of these systems is also difficult. Indeed, many (e.g. Cilliers, 1998) argue that distinguishing a complex system from its environment is, in the end, an analytic choice, i.e. determined by the purpose and perspective of the observer seeking to describe it, who is therefore an active participant in the construction of complexity.

Features of complex systems

Despite these challenges of delimiting and describing complex systems, there is more or less broad agreement as to their key features, which are summarized in Table 4.2.

Arguably, that which most distinctly characterizes a complex system is the set of

Table 4.1 Disciplinary origins of complexity science

Reference	*Discipline*	*Key Concepts*
European School		
Poincaré 1890	Mathematics	Non-predictability of nonlinear dynamic systems; three-body problem.
Bénard 1901	Fluid dynamics	Bénard cells.
Prigogine 1955, 1962, 1980	Thermodynamics	Nonlinear thermodynamics; non-equilibrium, dynamical statistical mechanics.
Popper 1959	Philosophy	Irreversible processes in physics.
Allen 1975, 1976, 1988, 1993a, b	Physics	Complexity and evolutionary adaptation modeled via stochastic systems dynamics.
Haken 1977	Synergetics	Synergetics; order & control parameters.
Eigen and Schuster 1979	Biology	Self-optimization; quasi-species.
Prigogine and Stengers 1984	Thermodynamics	New worldview implied by self-organization.
Favre et al. 1988	Fluid dynamics	Transitions of systems from turbulence to order; multidisciplinary perspective.
Cramer 1993	Molecular biology	Dissipative structures; chaos; multidisciplinary perspective.
Cohen and Stewart 1994	Biology; mathematics	Emergence of simplicity from the interaction of chaos and complexity.
Mainzer 1994	Philosophy	Order creation, from quantum physics and biology to the econosphere.
Prigogine (with Stengers) 1997	Thermodynamics	Arguments against reversibility of time, Einstein's determinism, and pure chance.
North American School		
Mandelbrot 1961, 1963, 1975	Mathematics	Fractal geometry; chaos; rank/frequency power laws.
Lorenz 1963, 1972	Atmospheric science	Strange attractors; sensitivity to initial conditions.
Kauffman 1969, 1993, 2000	Medicine	Spontaneous origins of biological order; fitness landscape models.
Holland 1975, 1988, 1995, 1998	Engineering	Genetic algorithms; emergence and coevolving agents; bottom-up science.
Thom 1975	Mathematics	Catastrophe theory.
Kaye 1989, 1993	Physics	Fractal geometry.
Arthur 1983, 1988	Economics	Self-reinforcing positive feedback processes in firms and economies.
Wolfram 1983	Computer science	Computational modeling of emergent structures.
Bak et al. 1987	Physics	Self-organized criticality.
Gleick 1987	Multidisciplinary	Chaos theory.
Pines (ed.) 1988	Multidisciplinary	Founding papers of SFI; Gell-Mann's 'surface complexity arising out of deep simplicity'.
Anderson et al. (eds.) 1988	Economics	Complexity applications to economics.
Langton 1989	Biology	Artificial life.
Lewin 1992	Multidisciplinary	Personalized account of the origins of complexity science at SFI.
Waldrop 1992	Multidisciplinary	History of the origins of complexity science at SFI.
Salthe 1993	Evolutionary biology	Self-organization in biology.
Casti 1994	Mathematics	Counterintuitive nonlinear surprises in all kinds of phenomena.
Depew and Weber 1995	Evolutionary biology	Evolution of evolutionary thinking from Darwin to self-organization biology.

From: Maguire et al. (2006: 168).

Table 4.2 Features of complex systems

1.	Complex systems consist of a large number of elements.
2.	These elements interact dynamically.
3.	Interactions are rich; any element in the system can influence or be influenced by any other.
4.	Interactions are nonlinear.
5.	Interactions are typically short range.
6.	There are positive and negative feedback loops of interactions.
7.	Complex systems are open systems.
8.	Complex systems operate under conditions far from equilibrium.
9.	Complex systems have histories.
10.	Individual elements are typically ignorant of the behavior of the whole system in which they are embedded.

From: Cilliers (1998).

interactions among its large number of constituent parts. These can be material/energetic or informational, and are typically, but not necessarily, rich and local. Individual parts, i.e. agents, respond in parallel to their local contexts according to some force or rule that relates their behavior interactively and contingently to the state of other parts. In so doing and without any part having a global view of the system or explicit coordination among parts, the parts can collectively give rise to system-level order which is not predictable from knowledge of the parts alone, through a process of upward causality. Once these emergent phenomena and properties are brought into existence, they can then exert influence on the parts through a process of downward causality, through the same set of forces or rules in place. Notably:

> although parts typically interact with neighboring parts, this does not prelude long-range influence nor self-regulatory loops of negative feedback, loops of positive feedback causing vicious or virtuous cycles, or some combination of these, as near-range interactions cascade forward in time. (Maguire et al., 2006: 166)

These possibilities mean that, for a complex system, time, in the form of a specific history, matters a great deal; the evolution of a complex system is typically characterized by path dependence and irreversibility. In addition, because interactions among agents 'may be characterized by non-linearity, which means that small causes are associated with disproportionately large effects in a system's state variables', complex systems 'display sensitivity to initial conditions, sometimes referred to as the "butterfly effect" after meteorologist Lorenz's (1963) claim that the flap of a butterfly's wings in one region of the world could affect weather patterns in others' (Maguire et al., 2006: 166). Gell-Mann (2002: 20) reminds us that 'the particular history we experience is co-determined, then, by the fundamental laws [of physics] and by an inconceivably long sequence of chance events, each of which could turn out in various ways' which give rise to a 'fundamental indeterminacy'; and, while 'most accidents in the history of the universe don't make much difference to the coarse-grained histories with which we are concerned', some become 'frozen accidents' by producing 'substantial effects, if only in a limited region of space and time'.

Complex systems thus give rise to emergence and complexity, and complexity science is the study of these phenomena. It offers researchers a set of concepts which is almost mathematical in its abstractness and potential applicability to a wide diversity of systems with different underlying ontologies and at different levels of analysis. For organizational researchers, for example, technology can be considered a complex system which evolves as new and existing artifacts are recombined (e.g. Fleming and

Sorenson, 2001); a single organization can be considered a complex system made up of individuals (e.g. Dooley, 1997) or of business units (e.g. Martin and Eisenhardt, 2010) or of value chain activities (cf. Porter, 1996) or, even more abstractly, of decisions (e.g. Rivkin, 2000); while a set of organizations, such as those making up an industry sector or the economy, can also be considered a complex system (e.g. Anderson et al., 1988; Arthur et al., 1997). In each of these 'wholes', it is possible for a coherent, mutually consistent ecology of interacting 'parts' to emerge from what is effectively a bottom-up and highly distributed process of construction.

Different views, types and aspects of complexity

'It would take a great many different concepts – or quantities – to capture all of our notions of what is meant by complexity', underline Gell-Mann and Lloyd (2004: 387). There is then, unsurprisingly, no agreement on how to conceptualize, define or measure complexity. Attempts to do so quickly encounter difficult ontological and epistemological questions which are made all the more intractable because they overlap. Is complexity an objective property of a given system in the world; or does it characterize an observer's subjective efforts to represent and make predictions about the system? Complexity is both and, therefore in some nontrivial sense, neither; the concept of complexity forces us to confront the limits – and hence meaning – of other concepts and their relations, including objectivity and subjectivity, among others. In other words, it leads us to confront the limits (Cilliers, 1998; Allen, 2000, 2001) – and hence meaning – of our knowledge.

One view, which happens to be the one that has dominated historically in organization studies, is that complexity is an objective property of a system and correlates with the system's structural intricacy (Moldoveanu, 2005), such that complexity increases with the number of parts as well as the density and variability of relations among them. Boisot and Child (1999) refer to this as 'relational complexity'. This type of complexity figures prominently in open systems models of organizations and contingency theory (Thompson, 1967), as a structural variable used to characterize organizations as well as their environments (Hall et al., 1967; Anderson, 1999). For example, organizational complexity has been conceptualized as proportional to the number of distinct organizational subsystems; and Daft (1992) recommends that it be measured using three dimensions: vertical, to capture the number of hierarchical levels; horizontal, to capture the number of units; and geographic, to capture the number of distinct sites. Similarly:

> in many empirical studies, the complexity of the organization is measured in terms of perceived coupling among sub-groups, tasks or procedures, the length of the process needed to go through to make a decision, or the number of people, resources or constraints involved. (Carley, 2002: 212)

As concerns organizational environments, it has been recommended to measure their complexity by the number of distinct entities to which a given organization must pay attention (Scott, 2002). More recently, scholars have operationalized complexity as 'the degree of interdependence among decisions that a firm faces'; and have viewed complexity as 'a feature of the environment in the sense that the interdependencies are dictated by the nature of the decisions themselves and … not chosen by the firm' (Siggelkow and Rivkin, 2005: 103).

These operationalizations, seemingly straightforward, hint at difficult issues however. For example, given that 'we may think of organizations as interacting networks of people, behaviours, routines, strategies, epistemologies, emotional states, cultural traditions, and so forth' and 'we may expect that within the same organizational phenomenon, multiple such individuations may arise, interact with one another and disappear', then 'this leaves in doubt both the essence of the modules or entities that make up the part-structure of the organizational whole, and the law-like-ness of the connections between these entities' (Moldoveanu, 2005: 259). Similarly, in identifying and enumerating the entities in an organizational environment to which an organization 'must' pay attention, the question arises: must pay attention why, or in order to accomplish what? These issues suggest that phenomena in the world and human describers of them are not as distinct as common understandings of scientific knowledge hold.

Standing in contrast to the structuralist view, an alternative view of complexity focuses on the observer of a system and argues that complexity is subjective: complexity correlates with the difficulty of representing and making valid or accurate predictions about the system (Moldoveanu, 2005), making it essentially an epistemological phenomenon. Boisot and Child (1999) refer to this as 'cognitive complexity'. Intuitively, we might expect a direct relationship between the objective, relational (i.e. structural) complexity of a phenomenon and the subjective, cognitive complexity experienced by an observer of that phenomenon. Indeed, implicit in the groundbreaking work of Simon (1962) on 'the architecture of complexity' is the assumption that relational complexity in the world translates into difficulties of representation and prediction in models of the world, i.e. into cognitive complexity. But this does not always hold: structurally intricate systems can behave simply and predictably (Bar-Yam, 1997); while chaos theory explains how structurally non-intricate systems can behave in unpredictable ways (Ott, 1993). In other words, because both emergent simplicity and emergent complexity are possible counterintuitive system-level outcomes, knowledge of a system's parts and their relations cannot be used to infer the complexity of the system as a whole (Bar-Yam, 1997).

Lloyd (2001: 7) catalogues 42 distinct measures of complexity and clusters them into three groups based on questions about the entity for which complexity is being measured: '(1) How hard is it to describe? (2) How hard is it to create? (3) What is its degree of organization?' These groups contain 11, 8 and 23 measures respectively. Based on the third question, one might expect that the third group would be comprised of measures of objective, structural complexity, but Lloyd's (2001: 7, emphasis added) inclusion in this group of those measures capturing the '*difficulty of describing* organizational structure, whether corporate, chemical cellular, etc.' underscores the challenges – if not the impossibility – of teasing apart views which posit complexity as an ontological phenomenon from those which posit complexity as an epistemological phenomenon.

In addition, Lloyd's (2001) first two questions point to different aspects of the difficulty facing an observer of complex phenomena. 'How hard is it to describe?' captures 'information' measures of complexity, typically quantified in bits; whereas 'how hard is it to create?' captures 'resource' measures of complexity, typically quantified using units of energy, time, computational resources, money or something similar (Lloyd, 2001). With information measures such as 'minimal description length', for example, 'the complexity of a system is associated with the degree of difficulty involved in completely describing the system' (Lloyd, 2001: 7). With resource measures, the complexity of a system is associated with the difficulty of constructing or duplicating or simulating the system, i.e. in manipulating and exploiting, typically for the purpose of prediction, descriptions of the system. For example, in computer science the 'computational complexity' of a task measures the amount of computing time or the computing capacity or the number of computing steps required to execute it. Similarly, measures such as 'crypticity' and 'logical depth' capture the effort necessary to produce knowledge then exploit it: 'In the human scientific enterprise, we can identify crypticity roughly with the difficulty of constructing a good theory from a set of data, while logical depth is a crude measure of the difficulty of making predictions from that theory' (Gell-Mann, 1995: 18). Although these latter measures are not, strictly speaking, information measures, they refer clearly to information processing activities and to activities of generating and applying knowledge. In so doing, these measures bear witness to the difficulty one faces in trying to disentangle the concepts of complexity and knowledge – the two are intimately connected.

Moldoveanu (2005: 263) argues for parsing the difficulty observers of complex organizational phenomena face into two components which map to these different dimensions and units: 'informational complexity' (also termed 'informational depth'), which 'relates to the minimum amount of information required to competently simulate or represent a phenomenon on a universal computational device'; and 'computational complexity' (also termed 'computational load'), which 'relates to the relationship between the number of input variables and the number of operations that are required by a competent representation of that phenomenon'. He underlines that a phenomenon is complex in the subjective difficulty sense if its representation in model form requires 'an amount of information that is at or above the working memory endowments of the modeler or observer; if the computational requirements of generating predictions about such a phenomenon are at or above the computational endowments of the modeler or observer; or both together' (Moldoveanu, 2005: 263).

Effective complexity

Gell-Mann (1994, 1995, 2002) points out that it is rarely a complete description of a phenomenon that is sought by an observer or modeler (which might be an agent in the world, such as a bacterium, a higher organism, an individual human, an organization, etc.); and argues that conceptualizations and measures of complexity based on a complete description do not, therefore, capture the essence of what is meant by the label 'complex'. He and his collaborators argue for the use of information measures because they 'are useful tools for dealing with complex systems: they can be used to measure both the amount of information needed to describe regular, rule-governed behaviour, and the amount of information needed to describe irregular, apparently random behaviour' (Gell-Mann and Lloyd, 1996: 45). Gell-Mann (1994, 1995, 2002) also argues that the essence of what is meant by 'complexity' is best captured by the concept of 'effective complexity' which, for a given entity, is an information measure defined as 'the length of a highly compressed description of [the entity's] *regularities*' (Gell-Mann and Lloyd, 2004: 387). This measure stands in contrast to another common information measure of complexity (Lloyd, 2001) – 'algorithmic information content' or AIC for short. Gell-Mann and Lloyd (2004: 388–389) explain, 'The AIC of a bit of string (and, hence, of the entity it describes) is the length of the shortest program that will cause a given universal computer *U* to print out the string and then halt'; and, in making their argument for focusing on 'effective complexity', criticize, 'Some authors call AIC "algorithmic complexity", but it is not properly a measure of complexity since randomness is not what we mean when we speak of complexity.'

Here, again, observers and modelers become implicated in the complexity of the phenomena of interest to them because, unavoidably, 'what is a regularity depends on a judgment of what is important and what is not' (Gell-Mann, 2002: 14). Mathematically, as Gell-Mann (2002: 15) argues, 'The best way to represent the regularities of an entity is to embed that entity conceptually in a set of comparable things, all the rest of which are imagined, and to assign probabilities or weights to the members of the set', because 'such a set, with probabilities for the members, is called an ensemble, and it embodies the regularities in question'. He shows that the AIC of an entity can be parsed into two quantities: *Y*, which captures the regular features, and ignorance, *I*, which captures the random features. *Y* represents the effective complexity of the entity if 'the right ensemble' is found, which is the ensemble that minimizes *Y* 'subject to the conditions imposed by the judge' or, in other words, 'based on a judgment of what is important' (Gell-Mann, 2002: 15).

If we consider an adapting and/or evolving entity such as an organism which is seeking to survive in an environment exerting selection pressures, then the regularities that matter are those in the organism's relationship with its environment that, once described, can be used in some way that leads the entity to generate 'behavior conforming more or less to the selection pressures in the real world' (Gell-Mann, 1995: 17). This is largely how the concept of 'adaptive agent' is understood within complexity science, as Maguire and McKelvey (1999: 42) explain:

> Be they organisms, humans, or firms, each of these can be seen to be surviving by compressing data and signals into 'internal models' or 'schema' of themselves, of their environment, and of the interaction between the two, and then 'exploiting' these to make predictions and to guide their behavior. Because models are never perfect or complete, all behavior also has an 'exploring' dimension to it as well: it generates more information that can be incorporated into and improve [an agent's] schema. Selection is multi-level, occurring on the level of internal models and behavior (i.e. learning as selection between competing schema), on the level of the agent (i.e. evolution as selection between competing agents), and perhaps on higher level 'organizations' that have emerged out of the interactions of agents.

Regularities result from both fundamental laws and frozen accidents: 'Frozen accidents, affecting significantly things judged to be important, give rise to regularities. Of course, the fundamental laws also contribute to regularities, but those laws are thought to be simple, and so effective complexity comes mainly from frozen accidents' (Gell-Mann 2002: 21).

If we consider humans or human organizations, however, the issue of identifying the regularities that matter – i.e. the issue of whose 'judgment of what is important' is to dominate, to borrow Gell-Mann's (2002: 15) phrasing – is rarely left, intentionally at least, for an environment to decide via selection. Rather, knowledge is brought to bear specifically to avoid, or to lower the probability of, being selected out by the environment. But, if the environment is truly complex then competing assessments of what is important, i.e. of the regularities that matter, are to be expected (see the chapter by Cilliers, this volume): 'since it is impossible to find all regularities of an entity, the question arises as to who or what determines the class of regularities to be identified' (Gell-Mann, 1995: 17). This situation, combined with the conclusion that observers and their representations (which should include and be a function of observers' *imagination* according to Gell-Mann (2002) and Gell-Mann and Lloyd (2004) are constitutive of complexity, suggests that complexity is not only inseparable from knowledge but also from a politics of knowledge as 'judgments of what is important' emerge from competing claims and vantage points.

It is well accepted that, in order to assess the complexity of a given phenomenon, the level of coarse graining and scale of observation must be determined; a certain amount of previous knowledge and understanding about the world must be assumed; and the language used in descriptions of the system under consideration must be agreed upon (Gell-Mann, 1995; Bar-Yam, 1997). Consequently, Gell-Mann (2002: 14) reminds, '[o]ne should recognize that effective complexity is context-dependent in a number of ways'; and he uses the example of men's neckties to illustrate. Those that are striped are intuitively less complex than those that are hand-painted, he argues, drawing upon an intuitive understanding of complexity as relating to the regularities in the neckties. Which regularities are discernible, in turn, depends upon how close to the necktie we are, i.e. the level of detail or 'coarse graining' at which we can, or wish, to describe the necktie. Regularities observed from across a room will differ from those observed under a close inspection with eyes just inches away from the necktie. Further, the level of complexity, as well as the ontology assumed by the language used to describe the necktie, depends upon who is describing the necktie and for what purpose: fashion designers and discerning customers will likely focus on features such as the presence or absence of stripes or hand-painted designs, the colors used and the relationship between these features and those of neckties which were part of prior designer collections; while dry cleaners will likely focus on other features such as the presence or absence of stains from food, wine or coffee, how extensive and intensive these are and the relationship between these features and those of neckties cleaned successfully and unsuccessfully in prior time periods. If assessing the complexity of a necktie is no simple matter, imagine the issues associated with assessing the complexity of a large organization, or an education system, or an ecosystem, or the economy.

APPRECIATING COMPLEXITY

Interpretations

Unavoidably, 'defining and understanding what constitutes complexity involves defining and understanding what constitutes information within, and about, a system', which 'raises the question of whose perspective, ontology and assumptions get to dominate, an obviously political matter when it comes to generating representations of and within social systems' (Maguire et al., 2006). Interpretive issues are not easily overlooked by natural scientists either because, even within a single epistemic community with a common epistemology and shared methodology, different levels of coarse-graining (i.e. scale of observation) can lead to, given emergent phenomena, different ontologies and hence different prescriptions for generating and applying knowledge about a given phenomenon. Advocates of scale-free theories, for example, face multiple fronts of resistance as each of the scientific communities which have a stake in defending their quasi-monopoly over knowledge claims at a given scale or level of analysis engage in defensive institutional work. When issues of interpretation are raised, it is common for natural scientists to seek to sidestep them by introducing the notion of intersubjective validity to replace objectivity; when interpretation is recognized as unavoidable, intersubjective agreement is posited so that researchers can get on with the task of building formal models. Such a maneuver is arguably less significant in situations of scientific disciplines 'where (1) the difficulty of reaching intersubjective agreement pales in comparison to that of representing and making predictions about a given system, and (2) the achievement of intersubjective agreement is conceived of as an apolitical act'; and more significant in situations where reaching intersubjective agreement is understood as a political process and also 'where the most difficulty – and, dare we say, complexity – resides' (Maguire et al., 2006: 171).

Competing, inequivalent descriptions have been viewed as constitutive of complexity by both natural and social science scholars. For example, Casti (1994: 276, emphasis in original) argues that 'the complexity of the system *N as seen by the observer* is directly proportional to the number of such [inequivalent] descriptions'; while Mikulecky (2001: 344) similarly argues that '[c]omplexity is the property of a real world system that is manifest in the inability of any one formalism being adequate to capture all its properties'. Thus the challenge of 'interpretive complexity' (Lopez-Garay and Contreras, 2003), which captures the difficulty of achieving intersubjective agreement on fundamentally interpretive issues, is in a significant sense prior to the difficulties faced by a single observer in compressing data to represent a system as well as those faced by the observer when subsequently computing predictions about the system. Casti (1994: 269) advocates defining complexity as 'a joint property of the system *and* its interaction with another system, most often an observer and/or controller'. Complexity thus can be seen to come into existence as particular representational frames are brought to bear on a specific phenomenon – a conceptualization that dissolves the object–subject and ontology–epistemology distinctions, much like post-structuralist approaches (see the chapter by Cilliers, this volume).

Strategies

Boisot and Child (1999) argue that there are two strategies for dealing with complexity – 'complexity reduction' and 'complexity absorption'. With the former, the goal is a convergent one of eliciting 'the most appropriate single representation' of the variety associated with complex organizational phenomena; while, with the latter, it is expected that actors 'can hold multiple and sometimes conflicting representations' of phenomena (Boisot and Child, 1999: 238). The goal of the latter strategy can be explicitly divergent – 'to generate new insights, and thus contribute to expanding the possibilities for thought and action' (Tsoukas and Hatch, 2001: 981). In a recent review of the literature on complexity and management, Maguire et al. (2006: 174–175) distinguish between more objectivist research which engages with complexity by reducing it and more interpretivist research which engages with complexity by absorbing it:

> In terms of the philosophy of science which underpins it, objectivist work tends towards positivism or those strands of postpositivism described as 'normal science' (Suppe, 1977; Curd and Cover, 1998; McKelvey, 2002). It adopts an information-based ontology and an epistemology premised on the existence and accessibility of objective information about a given system (or, less strongly, information that is intersubjectively agreed upon and valid). It employs a view of organizations and their members as information-processing systems or as adaptive systems coming to grips with some objective environment about which information that could help them to adapt can be ascertained. This work also tends towards quantitative research, mathematical formalism, and agent-based computational modeling. It also commonly considers representation as an apolitical act and scientific representations in particular as neutral. On the other hand, interpretivist work tends towards postmodernism or post-structuralism. It adopts a meaning-based ontology and epistemology, and is premised on the impossibility of identifying any information as objective. Rather, it views organizations and their members as interpretive, sense-making systems. More qualitative, this work is typically also more sensitive to the politics of representation as well as to the limits and provisional nature of knowledge about complex systems.

Morin (2007) makes a distinction similar to the reduction vs. absorption one of Boisot and Child (1999) by delimiting what he terms 'restricted complexity' and 'generalized complexity'. The former describes complexity as conceptualized by researchers seeking essential patterns in, and universal rules for, the phenomena they are investigating. Restricted complexity is captured and represented in mathematical formalism and computational modeling by researchers interested in dynamical systems called complex (Morin, 2007) and referred to by Richardson (this volume) as 'neo-reductionists'. This community of scholars recognizes but 'reduces' (Boisot and Child, 1999) or 'decomplexifies' (Morin, 2007) complexity and, in so doing, ultimately avoids 'the fundamental problem of complexity which is epistemological, cognitive, paradigmatic' such that 'the paradigm of classical science remains, only fissured', according to Morin (2007: 10). In other words, after a nod to the tough epistemological – and therefore, especially for social systems, political – issues raised by recognizing complexity, many researchers engage with complexity by re-embracing the 'Cartesian reductionism' with which they are comfortable (Mikulecky, 2001). In so doing, a constitutive aspect of complexity is lost: 'In fact, there is no way to capture real-world complexity with any finite number of formal systems and the limits of the Newtonian Paradigm are obvious' because 'the Newtonian Paradigm itself has been designed to exclude everything that real-world complexity embodies' (Mikulecky, 2001: 348).

Generalized complexity, on the other hand, represents a conceptualization of complexity that substitutes an emphasis on opposition and dualisms with an emphasis on mutual implication and dualities. Generalized complexity describes complexity as conceptualized by researchers who are reflexive about and accept that the object of their knowledge cannot ever be fully captured. Rather, by 'absorbing' (Boisot and Child, 1999) complexity, scholars understand their knowledge of phenomena called complex as provisional and contingent: its limits are explicitly acknowledged (Allen, 2000, 2001) and its method, conforming to 'the logical core of complexity', is 'dialogical' (Morin, 2007). As a consequence, science becomes re-contextualized and itself understood *historically* and *relationally* with other human endeavors, including philosophy, politics and ethics. Ongoing critical reflection on the nature and limits of knowledge is indispensable to the study of complexity (Cilliers, 1998, 2000).

Let us be clear: this is not at all to say that efforts to tame complexity by 'reducing' it (Boisot and Child, 1999) and rendering it 'restricted complexity' (Morin, 2007) through formalization and modeling are not useful because they adopt a reformative rather than revolutionary stance toward the epistemology and paradigms which dominate in science; it is to say, however, that these efforts need to be contextualized within a worldview that is reflexive about the choice not to 'absorb' complexity (Boisot and Child, 1999) – a worldview that appreciates 'generalized complexity' (Morin, 2007).

CONCLUSION

This chapter has introduced and explored the concept of complexity, highlighting how it has been constructed in different ways and is intimately bound up with issues of representation, prediction and interpretation. Perhaps 'complexities science' better captures the project in which complexity scholars are engaged, since appreciating complexity involves acknowledging that competing interpretations constitute it; and recognizing that the nature of the complexity with which one wrestles stems from one's framing of and strategy for interrogating it. Incentives exist to focus on restricted complexity at the expense of the big picture which is generalized complexity; and these need to be counteracted, as Gell-Mann (2002: 22) underlines:

> Unfortunately, in a great many places in our society, including academia and most bureaucracies, prestige accrues principally to those who study carefully some aspect of a problem, while discussion of the big picture is relegated to cocktail parties. It is of crucial importance that we learn to supplement those specialized studies with … a crude look at the whole.

Because the exploration of generalized complexity is a dialogic undertaking, it accommodates efforts to capture restricted complexity through formalism and computational modeling, but embeds them within a certain humility as well as a respect for both the phenomenon in question and other observers of it. Consequently, the phenomenon of complexity is potentially transformative of the science that made it an object of knowledge. There is, indeed, much to appreciate about complexity.

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5

Thoughts on Complexity and Computational Models

Michael J. Prietula

WHITHER COMPLEXITY?

What do we mean by 'complexity' when we discuss computational models of human organizations? In part, the answer to this question is the mission of this volume wherein many definitions and discussions can be found. However, an exact and particular answer to this question may not be straightforward, as we see definitions of complexity ranging from informal articulations of 'generic difficulty' to highly-constrained mathematical specification of certain and requisite properties. Consider that in 1988 a Complex Systems Summer School was held by the Sante Fe Institute in New Mexico, bringing together a wide range of scholars with the ultimate goal 'to advance research in the general science of complexity' (Stein, 1989:xvi). A derivative of that event was a book on the topics covered, *Lectures in the Sciences of Complexity*: *Volume I*, with contributors including Stuart Kauffman, John Holland, and Brian Arthur. The Preface begins with a humble statement: 'Complexity is almost a theological concept; many people talk about it, but nobody knows what "it" really is' (Stein, 1989:xiii).

Over twenty years later how have we done? In Melanie Mitchell's (2009) new book, she concludes that 'neither a single science of complexity nor a single theory of complexity exist yet' (p. 14) and 'many different measures of complexity have been proposed; however, none have been universally accepted by scientists' (p. 13). Is this lack of convergence either essential or important for organizational researchers? And, in particular interest for this chapter, what are the implications to the use of agent-based models in organizational research?

I suggest that the short answer to the first question is 'no' as there is no necessary requirement for the advancement of a discipline that demands a broad range agreement on a definition of a particular term, concept, law, theory, or metric that crosses disciplinary boundaries. Moreover, a fundamental problem exists in even defining what constitutes 'agreement' (i.e. beyond simple assertion) in that the ontological or theoretical stance, as well as broader context, may differ among them. Evolutionary theory (if we can even articulate an unambiguous definition) has qualitatively different operational definitions and meaning in biology than it does in (evolutionary) psychology than it does in organization theory.[1] Similar differences can be found for 'complexity' among (and within) the aforementioned three example disciplines. Therefore, to begin a discussion it is necessary to provide a sufficient definition or description, whether operationally or otherwise, that accommodates a particular disciplinary context, so that interpretive differences in the use can be accurately discerned. This, of course, is true for any cross-disciplinary effort and is certainly true for attempts like complexity that purport to cross several. From a good definition one can infer the nature of the agreement, and thus its implications.

We can generate a reasonably intuitive interpretation of what we mean by complexity in our current discussion. Complexity necessarily has at its core component *aggregation dynamics* – that is, the object under study is a system comprised of a collection of 'subparts' that interact (in some fashion) over time. What sorts of general properties characterize such systems? We might start with the following as four typical properties of such *complex dynamical systems* from the *physical sciences*:[2]

Property 1. *Structurally Aggregated.* The system is comprised of a group (or groups) of components – that is, there are sub-components involved in the system that contribute to, or define, the overall behaviour. These are the particles and planets of the basic physical science models. There may or may not be different levels of aggregation in the system.

Property 2. *Dynamical Interaction.* Subcomponents of the system interact – over time, components engage each other in some manner wherein the interaction has the capability to influence (i.e. change) subcomponent behaviours.

Property 3. *Invariant and Universal Rules.* In the basic physical sciences, laws (perhaps statistically defined) govern the nature of these interactions (e.g. laws of motion, laws of thermodynamics).

Property 4. *Component Homogeneity.* Any given sub-component is exchangeable with any other subcomponent; that is, any unique behaviour of any sub-component is attributable solely to historical path of interactions and not to any fundamental differences in sub-components (within categorical contexts). Individuality does not exist.

The concept of 'complex' dynamical systems describes those dynamical systems which are either difficult or impossible to tract and predict analytically. How difficult is it to create a complex dynamical system? Consider the three-body problem from classical mechanics. Imagine two objects rotating about each other where the sole influence on the paths of their behaviour are their initial relative positions and the mutual attraction of gravity. The paths over time for each object are analytically solvable – the objects generate elliptical orbits about the barycenter (the center of mass for the two particles). However, adding simply one more body makes things amazingly difficult. To date, researchers have not yielded an explicit expression for the general solution that permits such systems (with three or more objects) to be solved analytically.[3] The third interacting body generates path behaviours that are chaotic – single cases can be illustrated but not predicted. Therefore, the 'tricks' of statistical mechanics need to be employed which, in part, treat the detailed states of the system elements as unknown, with the presumed number of components approaching infinity, but subject to probabilistic description (Evans and Morriss, 1990). The specifics of the system need to jump from two to infinity in order to be tractable. If physics cannot address the specific path predictions of three or more interacting objects, what hope does our social science version have in explicating knowledge of our people interacting in organizations?

To examine this question, we need to revisit the properties of a dynamical system. When we consider aggregates of organizations composed of humans, this list of properties changes.[4] First, humans (and their organizations) are typically purposeful. That is, the assembly generally has overall goals to achieve (Barnard, 1938), but in human systems the concept extends beyond a property of the aggregate to the components of the aggregate itself (Ackoff and Emery, [1972] 2006):

> Both organisms and organizations are purposeful systems, but *organisms do not contain purposeful elements*. The elements of an organism may be functional, goal-seeking, or multi-goal seeking, but not purposeful. In an organism only the whole can display will; none of its parts can. (p. 222)

Purposeful elements of the organization define both the property and mechanism of valuation of the aggregate behaviour. Will, then, is an essential component of a purposeful system and its components underlying such definitions and valuations. What do they mean by 'will'? Essentially, will allows a system (or its components) to 'change its goals in constant environmental conditions; it selects goals as well as the means by which to pursue them' (Ackoff and Emery, [1972] 2006:31). In other words, a purposeful system is *adaptive*. With this additional property, we have defined a type of *complex adaptive system* (e.g. Mitchell, 2009), characteristic of virtually any living system.[5]

Property 5. *Adaptive*. Both systems and sub-components (humans) are driven by goals to attain within the context of a purpose.

However, as our sub-components are actually humans, the adaptive property is further specified as a component of 'will' in terms of goal-orientation, flexibility, choice, and learning. Thus, there is an aspect of adaptation that attributes substantial endogenous flexibility. The implications of these are significant, and two stand out. First, if individuality *does* matter then Property 4 above must be accommodated. Does it matter that individuals learn at different rates? Does it matter that individuals have different knowledge? Does it matter that individuals make different choices in the same situation? Does it matter that individual's have different influence over, or connectivity with, others? Does it matter that individuals have memories of the interactions in which they engage? Individuals may differ in significant ways either initially or as events unfold. Consequently, the nature of the interaction dynamics, and hence perhaps the overall system dynamics, lead to different behaviours – sub-components are not fully interchangeable. Thus path-dependencies may matter, as well as which individuals are on which paths, and matter perhaps significantly, in terms of the particular state of a particular sub-component and its interactions with others. We need to alter Property 4.

Property 4'. *Component Heterogeneity.* There are aspects of agents that differ, through initial endowments, consequences of interactions, or both, and such individuality can impact (ultimately) system behaviour.

Second, the rules guiding the system behaviour as well as the behaviour of the sub-components may be under-specified or variable (or both), necessitating revision to Property 3. In traditional physical sciences (e.g. physics, chemistry), these rules may be interpreted as laws, defined as mathematically expressed generalizations, often describing idealized systems, whose consequences are determined by implications of the expression(s) (Feynman, 1965). In fact, true chaos (as a mathematical concept) only occurs in deterministic, nonlinear dynamical systems, with one common definition is that which is deterministic in constants but unpredictable in variables, as is found in some nonlinear systems (Williams, 1997).[6] That is, looking at the underlying equation(s), one can supply values for the constants and input a value for each variable, and the result is predictable. However, predicting values over ranges of the variables as the system unfolds over time cannot be done. The search for chaotic properties is, in part, to discern underlying regularity in the presence of apparent noise.

In biological sciences, however, there is often a distinctly different approach, where generalizations are typically expressed (and characterized) as *theories* rather than laws (though the term may be retained), as described by Ernst Mayr (1988):

> Generalizations in modern biology tend to be statistical and probabilistic and often have numerous exceptions. Moreover, biological generalizations tend to apply to geographical or otherwise restricted domains. One can generalize from the study of birds, tropical forests, freshwater plankton, or the central nervous system but most of these generalizations have so limited an application that the use of the word law, in the sense of laws of physics, is questionable (p. 19).

Thus, as physical science generalizations are seen as (relatively) invariant and biological science generalizations are seen as contextual, what about generalizations of human behaviour? For the levels of scale of interest in this chapter (e.g. activities of deliberation and choice in human systems), our specification of relevant behaviours are not dominated by fundamental physical laws and invariances of nature. The theories we posit are not only contextual and based on the specific environment of interest (as are biological), but must accommodate the fact that these environments themselves are often artificial in nature and the 'laws' of interaction may change (Simon, 1969). From an individual's perspective, much of the environment is defined by other individuals who reflexively view that individual in their environment. For example, norms (Hechter and Opp, 2001) and broader issues of culture (Shore, 1996) as well as legal systems (Jolls et al., 1998) define highly contextual systems exerting substantial influence on the dynamics of interaction among individuals *that are both artificially constructed, recursively reflexive, and learned.*

Property 3'. *Variable and Contextual Rules.* Both structural and behavioural components are not only influenced by physical laws, but rules of interaction may be dominated by highly contextual, perhaps vaguely specified, and changing 'laws' that influence behaviour in direct and indirect ways.

Thus, the difficulty of discerning laws of human behaviour may seem ominous and the importance of this distinction is addressed by Scriven (1956), who asserts that there is no reasonable expectation that simple laws of prediction in the behavioural sciences will be found. The assertion is based on the belief that in even the simplest (but non-trivial) cases, there are multiple critical variables involved: 'The difference between the scientific study of human behaviour and that of physical phenomena is thus partly due to the relatively greater complexity of the simplest phenomena we are concerned to account for in a behavioural theory' (p. 332). Nevertheless, sometimes complexity can be more apparent than real (Table 5.1).

SIMON'S ALLEGORY OF THE ANT

Insight into the relationship between complexity and computational models of organizations can be gained in recalling Simon's *Allegory of the Ant* (1996), where an observer sees a singular wandering ant 'making his laborious way across a wind- and wave-molded beach' (p. 51). When one sees an abstracted graph of the ant's path, it appears exceedingly complex and most difficult to describe. However, as Simon points out, the complexity of the path is largely determined by the obstacles encountered by the ant, and not the complexity of the ant's choices of path formation. Therefore, to understand the likely path of the ant, the key is in the analysis of the ant's (presumably simple)

Table 5.1 Properties comparing physical and human complex systems

Physical systems	*Human systems*
Structurally aggregated	(Similar)
Dynamical interactions	(Similar)
Invariant and universal rules	Variable and contextual rules
Component homogeneity	Component heterogeneity Adaptive (intelligently)

locomotive adaptive system and its goal. Set the ant in a particular environment, and examine how it moves. Similarly, Simon asserts the relative simplicity of human behaviour:

> Human beings, viewed as behaving systems, are quite simple. The apparent complexity of our behaviour over time is largely a reflection of the complexity of the environment in which we find ourselves. (1969:53)

Consequently, to understand the behaviour of an individual, the key is in the analysis of the individual's (presumably simple) cognitive adaptive system and its goal. Set the human in a particular environment, and examine how the human behaves.

Let's modify the ant metaphor. Rather than ants wandering the beach under the influence of the environment, imagine that the ants are reacting not to other pebbles, but other ants, and every one of those are reacting to each other. If we watch these ants interacting, we get a substantial increase in apparent behavioural complexity, but again this is due to the nature of the increased complexity of the environment. As the ant moves through the maze of other ants, these ants may move, and the environment we are watching to predict the original ant's path is changing. Following Simon's arguments, the environment to which the original ant is responding includes the other ants. Furthermore, for any given ant in that environment, the other ants are responding to their environment, which includes all other ants including our original ant.

As we observe ants swarming, bumping into one another, altering their path, we again see complexity in path behaviour. Given the simple nature of the ants, are their collective patterns well-specified? Are there analytical solutions? Not really. The behaviour of the collective (e.g. a swarming raid pattern) is not explicitly contained in the ants' simple rules (Camazine et al., 2001). However, we do know that much of an ant's mobile behaviour is influenced by information contained in trails of pheromones, often bounded by behavioural goals (e.g. acquisition of food or prey), and density of nest mates. In fact, very precise swarming patterns can be generated through a computer simulation based on seven simple rules of behavioural engagement – how they react to their environment (Deneubourg et al., 1989). Ants have adapted their behavioural mechanisms for over 140 million years (Moreau et al., 2006) and virtually all of those mechanisms are likely genetically-based to engage in pre-defined behavioural typology to achieve pre-defined goals. Their behaviours, though slightly adaptable, are essentially invariant. Workers work. Queens breed. Soldiers fight.

But our rules of interaction are not so evolutionarily determined; rather, evolution has sort of reversed the mechanism – we are quite malleable in our behaviour. Again, substituting people for ants, people are in each other's (social) environment. Each person is reacting to an environment that is reacting to them. We (as hominids), however, have been around for about 6 million years after our divergence from other apes, but our brain size has increased four-fold since then until it stabilized about 100,000 years ago with its final increase under *Homo sapiens* (Lee and Wolpoff, 2003). The development of our neocortex in particular (and associated hyperconnectivity) suggests that this was a consequence of the need for engaging in social groups and all that entails, including communication, coordination, and deception (Byrne and Whiten, 1988; Dunbar, 2003; Dunbar and Schultz, 2007). The enlargement of the brain required that our infants be born when the skull is sufficiently pliable, which seems to extend aspects of cortical plasticity for several years (Julész and Kovacs, 1995; Elman et al., 1996). This plasticity allows for substantial influence of the environment (Quartz and Sejnowski, 1997), and much of that environment consists of people. Furthermore, this (extended) plasticity coupled with the capacity for language development (Pinker, 2002) affords important opportunities to acquire skills, writing, culture, and other related knowledge *symbolically* (Deacon, 1997), which is a substantially more efficient mechanism for learning than direct experience alone. At an early age, we learn how to adapt to a remarkably complex, and changing environment.

The end result is that we show remarkable flexibility in the behaviours we may exhibit. That flexibility is revealed in the artifacts that we design, such as organizations, but is also revealed in Simon's 'environment as mold' concept. Much of the work on organization theory is based on attempts to explain behaviours of individuals (individually and collectively) within the environment of an organization.

THE ORGANIZATION AS MOLD

Organizations in the form that we often explore are artifacts designed to achieve a goal. The goals will require divisions (or even subdivisions) of effort of individuals that can work together; that is, a 'defining characteristic' of an organization is that it is, in fact, organized (Cartwright, 1965/1997). As March and Simon put it, organizations 'are systems of coordinated action among individuals and groups whose preferences, information, interests, or knowledge differ' (March and Simon, 1993: 2). Now, where does the concept of complexity fit in this discussion? I suggest as examples that there are (at least) two that interact, complexity of *structure* and complexity of *function*, that have potential impacts on system behaviour with respect to its stability and serve to simply illustrate the point.

Organizations are computational devices. They are designed (explicitly or implicitly, successfully or not) to reduce both structural and functional complexity in order to attain sufficient forms of efficient stability in achieving its goals. Stability, in the context used here, is a qualitative assertion about a dynamic property of the system as whole, and not to a property of any specific component (Ashby, 1960).[7] Of course, there are many different interpretations of structure and processes, but my point here is to illustrate how two such important general constructs (no matter how they are defined) can have an impact on overall behaviour of the system and, consequently, its stability.

Complexity of structure

Structure involves conceptual or physical partitioning and describing how those partitions interact. This partitioning could be by function, geography, product or customer, but could be sub-partitioned (hierarchically scaled) and/or alternatively partitioned (perspectively scaled) based on other factors, such as authority, power and communication (Kates and Galbraith, 2007). Simon's concept of nearly decomposable systems illustrates, in the general form, the primary value in partitioning (1996: 197). The key word in this perspective, and related to partitioning in general, is 'nearly', wherein necessary paths of connectivity are retained. For example, in vision research this property is called 'weak modularity' (Kosslyn and Koenig, 1992). As Ashby (1960) notes, system stability 'always implies some co-ordination of actions between the parts' (p. 57). Structural complexity in organizations has classically been measured in terms of the number of partitions (Blau, 1971), but more sophisticated analysis takes into account multiple dimensions of structure (Scott, 1987; Burton et al., 2006). In general, structural complexity attempts to capture the aspects of partitions and their relations. For the most part, structural complexity is assumed fixed over a focused timeframe of interest, though not necessarily stationary over broader ones.[8]

Complexity of function

Function involves the fundamental processes engaged by individuals or groups within the structure. One option for discerning complexity may be a simple count of unique functions (e.g. Kannapan, 1995), or some derivative of that such as those used in software development (e.g. Symons, 1988). However, the nature of discerning the individual and collective complexity of functions is, in general, underdeveloped (McShea, 2000). A simple intuitive interpretation might include the amount of 'cognitive effort' (or task complexity) for an individual or group to execute (with indicative measures such as error rate or time to train). In general, functional complexity attempts to capture both the breadth and execution costs and difficulties for processes, under the broad title of organizational routines. For the most part, functional complexity is a dynamic entity describing those routines, and possibly the rate of change of those routines.

Now, let's return to the allegory of the ant/human. The two dimensions above exemplify the range of abstract environments formed by human organizations. We know that individuals or groups will adapt to their environment (under the correct motivations and opportunities) engaging routines that accommodate the demands of the environment (Nelson and Winter, 1982) as well as internal accommodations and constraints (Cyert and March, 1963). Look at the routines of an organization, and that will tell you a lot about the environment within which those routines reside. But also look at the behaviours of the individuals – that will also tell you a lot about the organization in which they reside (Simon, 1976). Despite the wide range of potential behaviours in which an individual can engage, their activities within an organization are actually quite limited by social, cognitive, individual and organizational constraints. For example, March (1994) describes how social identities define sets of rules that determine 'appropriateness' of actions, which then influence choice and behaviours for those adopting those social identities. This is what Carley and I (1994) refer to as the *induced simplicity hypothesis*, which suggests why much of the simplicity (and variance) in human behaviour is largely explained by (again) the characteristics of their environments, and generally those (organizational) environments call for behaviours that are simple and recurring. People will become the kind of decision maker that the environment affords.

One method of understanding aspects of how the complexity of environments contributes to organizational phenomena is the use of computational models that simulate the components, structure, and dynamics of the organization.

COMPUTATIONAL MODELS

Our interest is in computational modelling to understand complex systems of individuals is derived from the uses of models in general, which has been at the core of 'how science is done' in fields as old as physics. But even in the vaulted halls of physics, there are disagreements. Morrison (1999) discusses how physicists Paul Dirac and Henrich Hertz differed in their approach:

> … a theoretician like Dirac sees the world as governed by fundamental laws and invariances that the need for models becomes not only otiose but creates the unnecessary philosophical problem of determining whether nature is actually like one's chosen model. Hertz, the experimentalist, perceives nature as filled with enormous complexity and it is the desire to understand how it might be possibly constructed, that motivates his reliance on models. (p. 41)

From our perspective, universal laws are best approximate and contextual, so we might consider siding with Hertz on the value of models in understanding how nature (and we are part of nature) works. But what about the ultimate scientific goal of prediction? In his historical account of Arthur Burks' role with the Santa Fe Institute, Waldrop (1992) describes Burks' encounters with critics who define the value of a science solely in the ability to predict. Set in the context of discussing systems that are potentially chaotic and highly path-dependent, and thus impossible to predict, Waldrop asserts Burks' retort that 'predictions are nice, if you can make them. But the essence of science lies in explanation, laying bare the fundamental mechanisms of nature' (p. 39), and computational models are an effective method of articulating fundamental mechanisms, in physical, biological or social sciences.

For example, at one end of the spectrum, molecular dynamics simulations evaluate the complex dynamics of extremely small systems, such as quantum plasma phenomena (e.g. Misra and Shukla, 2009) and systems operating at nanosecond timescales (e.g. Duan and Kollman, 1998). At the other end of the spectrum, Sussman and Wisdom (1992, 1988) conducted computational simulations that demonstrated Pluto's orbit (covering 845 million years) is chaotic (1988) and a 100 million year simulation that demonstrates the solar system itself exhibits chaotic properties (1992). The first digital simulation of a complete life form (an all-atom molecular dynamics model of a virus) has been created and used to test its stability properties (Freddolino et al., 2006). The relative laws of consequence vary from solar system to virus, but if the relevant ones are captured computationally, substantial progress can be made on demonstrating the sufficiency of mechanisms underlying the behaviours of interest.

Gell-Mann (1995) provided an intuitive metric of complexity ('effective complexity') as the simplest description of a system's (observed) regularities that sit between none (entire randomness) and fully determined (e.g. closed form solution, analytically tractable). In our earlier discussion of the 'three-body problem', we noted a similar observation of extremes – those systems having a small number of sufficiently tractable components (call them, simple) and those systems with a few more components rendering them intractable (call them, complex). If we adopt Gell-Mann's pragmatic perspective, then we can begin to discern the role that computational models might play in generating insights in complex adaptive *social* systems. Specifically, if we engage an alternative investigative approach, wherein we remove the classification constraint based on analytical tractability, then that demarcation between the extremes of 'simple' and 'complex' disappears.

This situation is reminiscent of a point made by Allen Newell almost 40 years ago in his famous assessment of the state of experimental psychology, entitled 'You can't play 20 questions with nature and win' (1973). Newell argued that by following a strategy of positing (and consequently testing) phenomena in terms of their extremes (i.e. opposites) often fails to yield sufficiently cumulative science as such distinctions are generally illusory. Furthermore, articulating and testing binary extremes of posited phenomena usually lead to derivative ancillary or sub-phenomena which are subsequently asserted under the extreme model. One important element of Newell's suggestion was to build more 'complete' computational models that accounted not only for the phenomena of interest, but the broader context within which the phenomena resides, in order to tell a coherent story.[9] Thus, we can then analyze how the processes behave over a range of parametric values in-between the polarizing theoretical extremes. Along that line, Miller and Page (2007) specifically discuss the 'interest in-between' in computational modelling complex adaptive social systems:

> Modelling, by its very nature, is about extremes … Unfortunately, sometimes in the pursuit of extremes, we kill off the most interesting parts of the world … One important insight from models of complex adaptive social systems is the interest in between the extremes. Using these models, we are finding that as we move away from the extremes we do not incrementally approximate what has come before, instead are thrust into new realms of experience. (pp. 227–228)

This is a nice articulation of what most computational social science is about – it is about things that occur somewhere between organization science's own version of the three-body problem and infinity. This perspective is also consistent with Merton's ([1949] 1996) assertions regarding middle-range theories of social phenomena, which is actually what most organizational theories are about:

> … theories that lies between the minor but necessary working hypotheses that evolve in abundance during day-to-day research and the all-inclusive systematic efforts to develop a unified theory that will explain all of the observed uniformities of social behaviour, social organization, and social change. (p. 41)

Putting it all together, there are several indications in theory and practice, across disciplines, that computational modelling is not only plausible, but a legitimate, or even necessary, methodology for advancing organization science.

COMPUTATIONAL ORGANIZATIONAL MODELS

If we presume legitimacy, then what are the potential benefits of a computational model in representing complex adaptive social systems capable of exhibiting complexity, such as organizations? Since our early edited volume on this topic (Carley and Prietula, 1994), there have been a variety of recent publications addressing this and related topics (e.g. Epstein, 2006, 2008; Davis et al., 2007; Harrison et al., 2007; Carley, 2009) including those in this volume. For the purposes of this chapter, I suggest that there are five (not unrelated) significant ones, which address the properties noted in Table 5.1, plus important characteristics of computational modelling itself.

First, computational modelling allows one to focus on multiple types of organizational phenomena that 'go together', most often in some mid-range theoretical context. As such, these mechanisms can employ multiple levels of associated representations with the breadth and depth that often generate substantial complexity in social science structures. Furthermore, the key properties of these mechanisms can vary – that is, we can assert heterogeneity in each of these mechanisms, if necessary, to allow specific types of variance in the population. Thus, aggregation can occur over multiple, possibly heterogeneous, constructs. In general, there *can* be an important characteristic of theoretical coherency that is attained in computational models. In discussing research on computational models of vision, Marr (1982) asserts that 'almost never can a complex system of any kind be understood as a simple extrapolation from the properties of its elementary components' (p. 19), and proceeds to conclude that 'if one hopes to achieve a full understanding of a system … then one must be prepared to contemplate different *kinds* of explanation at different levels of description that are linked, at least in principle, into a cohesive whole' (p. 20). Thus, and again reminiscent of Newell's warning, Marr does not assert a pure 'reductionism versus holism' distinction, but a view that accommodates phenomena across these perspectives, similar to the hierarchical reductionism arguments now found in biology (Dawkins, 1986). Depending on the nature of the question, one can subsequently test for regularities or invariants across levels or contexts (Simon, 1990; Gell-Mann, 2002).

For example, Ashworth and Carley (2006) demonstrate this nicely in their simulation of impact of individuals on team performance, where they integrate constructs such as social network structures, task attributes and individuals' knowledge. Boero et al. (2008) show how a small difference in the cognitive features of individual agents (i.e. heterogeneity) can lead to remarkably different macro properties. Carroll et al. (2006) incorporated complex elements of an actual case to simulate alternative organizational designs.

Second, one can focus on the process as well as the product of behaviour. Computational modelling defines a set of mechanisms operating dynamically, concerning both individual and collective behaviour, over time. That is, we can make a distinction between the interim events of the model's components and the more generic properties of the collective consequences of those components.

We can get traces of behaviours as the simulation dynamically unfolds. This, of course, is a reductionist type of argument, but one that permits doing social science 'from the bottom up' (Epstein and Axtell, 1996). Although there may be overall questions of attributing ultimate causality in nonlinear systems (e.g. Wagner, 1999), capturing the dynamics of interaction of the mechanisms can generate plausible evidence of causality through demonstration of mechanism sufficiency to account for the phenomena one is attempting to explain. For example, Ethiraj and Levinthal (2009) examine the average performance over time under conditions of whether goals are temporally differentiated or not. With components of the underlying dynamics specified, we are likely more insulated against the risk of making the ecological fallacy of drawing false inferences about individuals, derived solely from aggregate data (Robinson, 1950).

A third benefit is the fundamental symbolic nature of the computer and the particular type of universality of the computational mechanism itself. Computational theories can capture both numeric and symbolic representations and processes; consequently, mappings from the theoretical constructs to computational representations can be made more efficiently. Furthermore, the representations of constructs when they are processes (as algorithms) have an important property. The concept of representing symbolic rules/routines or any other algorithm, whether they are descriptive of individual deliberation (e.g. decision rules and preferences, a specific underlying cognitive architecture), an abstracted aggregate (e.g. group, division, organization), or any intermediating model or simulation architecture (e.g. *NK*-landscapes, Swarm, NetLogo, RePast, systems dynamics) can be sufficiently and equivalently captured by a computational model, which has remarkably powerful theoretical limits and equivalence (Harel, 1989; Sipser, 1997). This is especially useful when the 'rules of behaviour' of the system, or of any system component, or any structural or process variation within either may change dynamically. Ironically, the universality of what *can* be simulated means that there are few constraints imposed on what *should* be simulated. Consequently, as computational models spread, there is no doubt the risk of insufficient substance hidden in the complexity of the form, generating a trivial computational *Gedankenexperiment*. Again, general guidance from Newell, Gell-Mann and Simon serve to promote the type of scientific perspectives that can orient the work and balance the simplicity of the model against the value of its (informational) return.[10]

The fourth benefit I find is another intrinsic property of computational models. Computational models permit postulated mechanisms to be manipulated explicitly. This is characteristic of much of the work in recent computational modelling, often cast as a computational experiment, systematically examining parameter spaces. For example, Lin et al. (2008) manipulate several types of search strategies exploring strategic network dynamics, Rodin (2008) examined March-like models learning under differing structural forms, and Fontaine et al. (2011) examine how culture and knowledge impact post-acquisition performance in a March-like model of learning, and Levine and Prietula (2011) incorporate multi-method (qualitative analysis of a knowledge sharing resource) with computational modelling, manipulating the parameters obtained from the field data in a simulation. The work of Epstein and Axtell (1996) remains one of the clearest examples of systematic manipulation of constructs that also includes multiple level modelling, and Harrison and Carroll's (2006) body of work on simulating organizational culture demonstrates how insight can be gained through coordinated sets of experiments. Included in this benefit are those categories of manipulations that can be called 'counterfactuals' – given a set of preceding events and the outcome, how would things change if the preceding events changed? This type of non-monotonic logic has been the study of philosophers (Collins et al., 2004), computer scientists (Ginsberg, 1986), as well as psychologists, social psychologists, and neuroscientists alike (Baird and Fugelsang, 2004; Mandel et al., 2005; Epstude and Roese, 2008). From an organization science perspective, this type of reasoning is often engaged in asserting attributions of risk, loss, or causation (e.g. Lipe, 1991) driving strategic and policy choices of organizations and governments. Formal manipulations and derivatives of consequence would seem as a more rational alternative than simply relying on the biased and boundedly rational methods of a 'mental simulation' (e.g. Kahneman and Tversky, 1982). Consequently, manipulating parameters in a computational form can more effectively accommodate counterfactual alternatives.

The final benefit I find is that building such models enforces a uniformity and formalism (i.e. 'uniformalism') in describing organizational phenomena. Though tractable, analytic solutions may not exist, the next best thing would be tractable, computational solutions. Computational models tend to be 'homunculus resistant' as the task of specifying the properties and behaviours of the model computationally requires the articulation of every important component – those that are not represented are simply not components of the theory. That is, these models tend to be unforgiving when under-specified. However, there are issues regarding how different levels of articulation can add to the understanding of organizational phenomena using computational models. This is addressed in the next section.

LEVELS OF SPECIFICATION

Computers are representational devices. Therefore, I will make a strong statement regarding computational models and the representational formalisms – in the *algorithm* resides the theory. This is an important point. Again we can turn to Marr (1982) for guidance on linking theory and computational models. In his discussion on vision, he argues that one needs to understand an information processing system on three levels, in order to claim that one 'understands' an information processing device (i.e. vision) completely. I suggest that this applies to understanding organizational systems as well, as they are also information processing devices (Simon, 1996). Table 5.2 indicates the levels from Marr's context (any computational device) adapted to our context (computational organization theory).[11]

At the top level, *Computational Theory*, there are theoretical statements that address the type of problems covered by the theory. Computational theories are about dynamics, and dynamics necessitate computation – therefore, it is important to assert *what* is being computed (and, of course, why). Marr, as did Simon, recognized the importance of studying the environment, noting that 'trying to understand perception by studying only neurons is like trying to understand bird flight by studying only feathers: It just cannot be done' (1982: 27). Again, if we understand (and specify) the environmental context, we are better prepared to understand the nature of the algorithm (i.e. dynamic processes, routines) and its role in organizational decision making. For example, in Cyert and March's behavioural theory of the firm, one of the key organizational processes asserted is organizational learning. At the computational theory level, this is asserted as three constructs: adaptation of goals, adapting in attention rules, and adaptation of search rules (1963: Chapter 6). Considering attention rules, one example addresses how profit goals are adjusted with respect to prior performance (i.e. last period's profit) and prior aspirations (i.e. last period's goal). From a theoretical perspective, the constructs and their general relationships are described.

Next is the *Algorithm* level, where fundamental choices are made in what constructs are represented (and how), what dynamics are defined (and how) in the model, and how they interact. I suggest that this level is critical for computational organizational modelling, as *at this level is where the theory* *is specified*. However, this is often insufficiently described or even absent from the discussion. The problem is that there are a wide variety of options for both representing constructs and defining the algorithmic dynamics. Furthermore, even apparently minor modifications in either can have impacts on the resulting behaviour and performance – if learning is involved, what form of learning function is used? What does search mean and look like? There is no 'coding' at this level, only descriptions of modelling choices. For example, in our computational models of Cyert and March's duopoly (Prietula and Watson, 2000), we used a pseudo-code type of algorithmic description to achieve this end.[12] This would be what Lucas (1980) called, in his description of business cycle research, 'an explicit set of instructions for building a parallel or analogue system – a mechanical, imitation economy' (p. 697). Referring back to the Cyert and March example, there are five constructs specified: profit (PFT), profit goal (PFG), two attention parameters (β_1, β_2), and a learning rate (η). Furthermore, there is a decision routine that specifies how they work together. Collectively, the algorithm forms the *operational definition of the theory*. Thus, 'attention' is operationally defined as a parameter that weighs the contribution of a variable (either profit or profit goal) to the aspirations for the next period. In fact, Cyert and March do include an Algorithm level in their specification, including verbal descriptions and flow-charts.

Given the Algorithm specification of the key constructs, there is the subsequent translation of the algorithm into executable forms via an *Implementation* level, where the *what* of the algorithm level is translated into the *how* of an Implementation level. For example, depending on the type of model, one can build a full model using straight code, such as Java, Visual Basic.Net, or C++; one could apply computational tools such as Mathematica (Wolfram, 2002) or MATLAB (Klee, 2007); or engage specific types of higher level development environments, such as NetLogo (Wilensky and Rand, in press), Repast (North et al., 2006), systems dynamics (Sterman, 2000), or Swarm (Bonabeau et al., 1999). The choices here are important as they can impose substantial constraints and implicit assumptions not articulated at the algorithm level. In the parlance of classic software engineering, here is where there is a distinct risk of verification failure – one fails to 'build the system correctly' given the specifications (Boehm, 1981). The literature is beginning to address some of these latter issues. For example, North and Macal (2007) present an excellent overview to agent-based model development where verification (and validation) is covered.[13] From a broader perspective, Ashworth and Carley (2007) argue that computational modelling tools can help unify organization theory by affording sharing tools created and, in fact, would facilitate building, replicating, and consequence verifying models extant in the literature on a common ground. Cyert and Marr's Implementation level was accomplished by a programming language called Gate, rendering comprehension of the actual model a challenge for the times (Augier and Prietula, 2007; Prietula and Augier, 2011).

Finally, there is a recurring discussion of whether 'code' should be made available or not for such research (i.e. the Implementation level of Table 5.2). My suggestion is that it should not; rather, the algorithms should be made available, similar to what is often encountered in computer science, specified as pseudocode (see note 12). I have two reasons for this suggestion. The first is pragmatic – who wants to delve through someone else's code? Not only are there potential proprietary issues, but examining the code is equivalent to *observing* the details of laboratory practices Bankes (2009) suggests that computational models are a type of laboratory equipment. This is very different from standard scientific reporting practices that communicate procedures by *defining* what laboratory methods, materials, and protocols

Table 5.2 Adaptation of Marr's (1982) levels understanding to computational modelling of organizations

Specification level	*Description*	*Example (Cyert and March, 1963)*
Computational theory (process model usually expressed verbally)	What is theory attempting to explain? What is the nature of the problem being solved? What theoretical constructs are addressed? How are they related? What is the logic of the strategy by which the dynamics are carried out?	Organizational learning is realized through: adaptation of goals, ***attention rules***, and search rules. Past performances will influence where (and how much) attention will be paid in future decisions. Attention paid to prior ***profit goals*** in formulating new profit goals will be based on ***prior performance*** and ***prior decisions*** of the near past. The ***rate of adaptation*** is determined by a constant for the firm.
Algorithm (process model expressed in structured computational form)	What specific constructs are represented? What are the underlying process(es)/ routines *that incorporate* the constructs and specify the dynamics? How do they interrelate?	PFT = profit made at end of time period t PFG = profit goal for time period t β_1 = attention paid to recent performance success (PFT) β_2 = attention paid to recent performance failure (PFT) η = second-order learning rate ($0.0 \leq \eta \leq 0.3$ rectangular) *if* $\{PFT_{t\text{-}1} > PFG_{t\text{-}1}\}$ *then* $\beta_1 = \beta_1 + \eta(1\text{-}\ \beta_1)$ $PFG_t = (1\text{-}\ \beta_1)PFG_{t\text{-}1} + \beta_1 PFT_{t\text{-}1}$ *else* $\beta_1 = \beta_1\ \text{-}\ \eta\beta_1$ $PFG_{t\text{-}1} = (1\text{-}\ \beta_2)PFG_{t\text{-}1} + \beta_2 PFT_{t\text{-}1}$
Implementation (process model realized in executable form)	How is the algorithm realized computationally? What are the mechanisms and how do they work? Which mechanisms are part of the theory and which are not?	;K29 ← K29 + 1; C78 ← (1-C132)*C78 + C132*C75 ;C131 ← C131*(1-C120) IF C75 < C78 C78 ← (1-C131)*C78 + C131*C75; C131 ← C131 + C120*(1-C131)

were employed. On the other hand, the key elements of consequence reside in the Algorithm level, where the interpretation of the theory is most clearly articulated as assumptions and intent – as I noted, how things are operationally defined. In the true manner of science, communication of the Algorithm is akin to a description of the detailed protocols of an experimental context, wherein replication of the protocol, through its description, should result in a replication of the findings. If the Algorithm can be replicated across Implementation choices, then evidence can naturally begin to accumulate surrounding a theory (to the extent that replication in social science is viewed as acceptable).

CONCLUSION

The purpose of this chapter is to serve as an essay for thoughts regarding complexity and computational models of organizations. The examination of Simon's Allegory of the Ant suggests that an environment of individuals will complicate the prediction of reactions, as the environment becomes increasingly complex. However, the flexibility of human adaptation is likely exploited by the constraints of the organizational context (induced simplicity hypothesis) that turns attention again to the environment as both mold and explanans for behaviours (see also Gigerenzer, 2007). Thus, the use of computational models of organizations is seen as not only viable, but essential for advancing aspects of organization science in attempts to bridge the macro-micro level of specification. In the words of Cohen and Cyert (1965/1997), such models can be based on 'reasonable assumptions', where:

> … the computer model is a model in which the implications of the assumptions, that is, the conclusions, are derived by allowing an electronic digital computer to simulate the processes embodied in the assumptions (p. 307).

Therefore, even if there is an equilibrium value, and many times there is not, the matter of interest may be in examining the path dynamics by which the equilibrium is reached.

As we are told of the physical examples of unpredictability and chaos from simple dynamic systems all around us (as pointed out by many popular books on the topic), one wonders how something as complex as an assemblage of humans can ever get anything done at all! I believe there are two reasons for this. One is that the organizations we study are generally (and relatively) stable structures, and the adaptability of humans (individually and collectively) within the realms of the extant routines generally serves to sustain the stability of the structure across a wide variety of disruptive forms (Simon, 1976).

The other is that our evolutionary past and cultural history seems to include roots of cooperation and empathy (Henrich et al., 2004; deWaal, 2009). Therefore, being a complex adaptive social system may not unequivocally require any of the 'maladaptive' properties of physical systems. As Snowden and Boone (2007) point out, there is a distinct difference between complicated, complex and chaotic states in an organization, and knowing that difference matters. I tend to agree with the observation that evidence for true chaos and complexity (in the mathematical sense) in real world data, versus idealized conditions, is difficult (Williams, 1997). Nevertheless, we do find things that closely resemble such behaviour in our social environments. As a consequence, we must understand the differences in context, and determine how to adapt such constructs *mutatis mutandis* to our social ones (e.g. Arrow et al., 2000).

Finally, we must make a distinction between our cognitive limitations to understand something (i.e. it is 'complex' because I cannot understand it), and ascribing measurable properties characteristic of complexity to phenomena, independent of any observer (i.e. it is 'complex' because is satisfies these conditions). In science, as Lord Kelvin asserted, measurement matters. Computational models can help distinguish between the two as well as facilitating the former and demonstrating the latter.

NOTES

1 For example, organizational theorists often mistake Lamarkian for Darwinian doctrine. In Lamarkian heredity, a behaviour (e.g. giraffe's 'stretching' their necks) or an exogenous alteration to phenotypes (e.g. cutting tails off of mice) will have direct genotypic consequences (i.e. longer necks, no tails). On the other hand, some theorists seem to avoid the necessity of genotypes (i.e. offspring) in their entirety, eliminating the fundamental elements underlying biological evolutionary mechanisms (i.e. 'organizations evolve'). Cross-disciplinary 'borrowing' of concepts should distinguish between metaphor and attribution. Raman and Prietula (2010) provide an example of comparing how a physics-based model of preferential attachment in network emergence generates different results from one incorporating a specific social science property (homophily).

2 List adapted from Holland (1995) and Mitchell (2009).

3 See Barrow-Green (1996) for the story of Poincare's essay on this famous problem, which contained a critical error. When correcting this error. Poincare discovered the foundations of mathematical chaos. For 300 years, the fundamental theories of physical sciences were based on analytical models involving two variables, with very minor extensions up to five (Weaver, 1961).

4 Note that other types of living systems may exhibit such properties, but we are focusing on human systems in this chapter. Furthermore, analysis of aggregates of humans may not necessarily require such properties under certain conditions and assumptions.

5 Mitchell (2009) also makes a point that there is no central control. As this is typically not the case in organizations, it is not pursued in this chapter.

6 Of course, individuals are also physical systems. The distinction is more one of what is being examined on what level, what timescales are of interest, and what constraints (via physical components) are imposed (Newell, 1990).

7 Interpretations of stability can range from exact forms of equilibria to less formal judgments of 'acceptable' regions of behaviour.

8 For example, in the duopoly model of Cyert and March (1963), the particular loosely coupled modularization of decisions was seen as changing as they argued that the firm was indeed an 'adaptable institution' (p. 99), but it was assumed stable over their simulated time frame of 50 periods.

9 Newell did not intend for this to be a new guide to science, but a caricature of the current state of experimental psychology. In fact, as science progresses, this form of questioning can indeed be locally efficient (e.g. Kosslyn, 2006).

10 As Newell used to consistently remind us in our research meetings, 'hypotheses come from the theory, not the theorist.' In Kydland and Prescott's (1996) discussion of the value of computational experiments in economics, they echo Lucas's (1980) advice in emphasizing the role of building on 'well-tested theory' in deriving components of the model.

11 This section is adapted from Prietula (2010).

12 Pseudocode is not actual computer code (e.g. JAVA or C++) and there is no universally accepted specification of 'the one way' to do pseudocode. Rather, it is a structured, English-like language that incorporates basic programming constructs (e.g. sequencing, decision, iteration) and uses 'whatever expressive method is most clear and concise to specify a given algorithm' (Cormen et al., 2009:17). The main goal of pseudocode is to effectively communicate the fundamental elements of an algorithm in an unambiguous manner so that the algorithm can be replicated in any language, yet yield to types of formal analysis.

13 See also Burton (2003), Burton and Obel (1995), Galan et al. (2009), Midgley et al. (2007), Thomsen et al. (1999).

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B

Epistemological Perspectives and Considerations

6

A Scientific Realist Epistemology for Complexity Science

Bill McKelvey

> There is no accepted definition of emergence, even among scientists, but few who have seriously studied such phenomena believe it to be an 'eye-of-the-beholder' effect. Indeed, it is possible to list criteria that go far toward distinguishing some observation as emergent, regardless of the observer and the time of discovery. (Holland, 2002: 27)

I subscribe to Holland's view that phenomena – whether compressible or not – exist in the real world independently of the *eye of the beholder*. This is the essence of scientific realism; it is possible to base truth claims on aspects of the real world, given appropriate research methods. My modification is that I substitute Campbellian Realism in place of the 'scientific realism' emanating from philosophies of science rooted in physics (McKelvey, 1999). It is important, however, to also take note of Gell-Mann's '*effective complexity*': Designing buildings in California is more complex because of earthquakes. The simpler building codes in, say, Texas, are ineffectively complex for California. On the other hand, one doesn't need to understand nano-phenomena to build quake-safe structures; nano-thinking would not be effectively complex either. Building codes – building 'schemas' as Gell-Mann (2002: 16) would call them – need to be effectively complex, no more no less.

Effectively complex theorizing and model-building, and doing the kind of research that produces effectively complex managerial schemata, are the objectives of effectively complex scientific method. Philosophies of scientific realism aim to accomplish this. Truth-claims, then, are also effectively complex. As you will see, in Campbellian Realism, while idiosyncratic perceptions of the phenomenal world are recognized, and social construction by scientific communities is accepted, ultimately good science is held accountable to the hard reality of what is real. Postmodernism, constructivism, and relativism undoubtedly surface at the beginning of inquiry, but *effective* complexity science applied to organizations and management needs to rise above these pseudo-science wishful-thinkings if truth claims are to be valid and believable. Nothing less will do! For the most constructive connection between postmodernism (really poststructuralism) see Cilliers' book, *Complexity and Postmodernism* (1998).

CRITIQUE OF POSITIVISM AND POSITIVIST ECONOMICS

Defining logical positivism and logical empiricism

> … The word 'positivist', like the word 'bourgeois', has become more of a derogatory epithet than a useful descriptive concept, and consequently has been largely stripped of whatever agreed meaning it may once have had (Giddens, 1974: ix).

In fact, 'positivism' has both strong and weak points and how it is defined has evolved. Positivists worry about the fundamental dilemma of science: *How to conduct truth-tests of theories, given that many of their constituent terms are unobservable and unmeasurable, seemingly unreal, and thus beyond the direct first-hand sensory experience of investigators?* The term, *positivism*, was coined by August Comte. He attempted to avoid the dilemma by disallowing into science terms not directly apparent to the human senses. Comte claimed that the goal of science is prediction based only on observable terms (Audi, 1995: 147).

Following Newtonian mechanics, German *mechanistic materialism*, held that '… existence obeys, in its origin, life, and decay, mechanical laws inherent in things themselves, discarding every kind of supernaturalism and idealism in the exploration of natural events' (Suppe, 1977: 8, quoting Büchner, 1855). It rests on empirical inquiry rather than philosophical speculation, a view in which there is no doubt that a real objective world exists. Materialism gave way to the neo-Kantian view that 'science is concerned to discover the general forms of structures of sensations; the knowledge science yields of the "external worlds" is seen as webs of logical relations which are not given, but rather exemplified … in sensory experience' (Suppe: 9). Thus science discovers not just the structure of matter but rather the *logic* of the interrelations among the phenomena. This view had become the dominant philosophy of the German scientific community by 1900. By mid nineteenth century Hegel's philosophy of 'the identity of reason and reality' dominated. It proclaimed only 'reason' is 'real', denying the existence of tangible entities such as earth, water, and fire. The world is purely perception, a matter of the mind!

Mach added the notion that scientific statements must be *empirically verifiable*, resulting in *neopositivism*. The excesses of Mach's approach, which included a rejection of mathematics, subsequently were denied, resulting in a *modified positivism* (Whitehead and Russell, 1910–1913) that still held to verifiability as a basis of assuring truth but included mathematics as an appropriate expression of scientific laws. During the ensuing decade the main elements of the *Received View* developed and were published in Carnap's (1923) first publication. It formally stated the tenets of *logical positivism*, since it included mathematical, theoretical, and observational languages as well as the separation of theory and observation terms.

By 1910 the Vienna Circle (founded in 1907), a group of Germans trained in logic, mathematics, and physics meeting at the University of Vienna, had accepted the task of considering how to respond to: (1) Hegelian idealism; (2) scientists' beliefs in mechanistic materialism; (3) neo-Kantian sensory experiencing of the external world; (4) Machian neo-positivism's emphasis of verification, and finally the crowning blows; (a) Planck's quantum mechanics; and (b) Einstein's theory of special relativity, both of which violated determinism, sensory relevance, and verificationism. Their official manifesto, *The Scientific World View: The Vienna Circle*, was published in 1929.[1]

Responding to the philosophical dilemma, logical positivists founded their epistemology on axiomatic theories, using terms comprising three languages: '(1) logical and mathematical terms; (2) theoretical terms; and (3) observation terms' (Suppe, 1977: 12). Theory terms are unreal, abbreviated representations of phenomena described by the observation terms. *Correspondence rules* (C-rules) assure theoretical terms are explicitly linked to observation terms. They held that theory terms are unreal and, thus, theoretical explanations of causality are also unreal, leading to the view that theories may be interpreted only as *instrumental summaries* of empirical results (Hunt, 1991: 276–277). The 'scientific truth' in theory terms is ascertained via '*verification*' in observation terms. Logical positivists attempted to clarify the language of science by expunging metaphysical terms not amenable to direct sensory testing and by insisting that logic terms be verified as to cognitive meaning and truth, thereby 'ridding it [science] of meaningless assertions by means of the verifiability principle and reconstructing it through formal logic into a precise, ideal language' (Hunt, 1991: 271).

In his classic statement Schlick (1932/33)[2] focused on the seeming impossibility of ever knowing whether the external world is different from the metaphysical or transcendent reality of the human senses, that is, cognitive construction or interpretation. In his view the only way to tell if some datum is real or not is to take it away and see if there is a difference. Thus, if I sit once and the chair is there and if I sit again and the chair is not there and I fall, I may conclude the chair is real. This is what Schlick refers to as a *testable difference*.

Subsequently Nagel (1961), and Hempel (1965), following others, evolved an epistemology focusing on *laws*, *explanation*, and *theory*, known as *logical empiricism.* It had replaced logical positivism by mid twentieth century. The logical empiricists' immediately encountered a problem with the verifiability principle, since for a law to be verified it must be empirically proved universally true for all times at all places, an impossibility. Consequently verifiability was abandoned, to be replaced by a somewhat relaxed *testability criterion* that all propositions have to be amenable to some measure of empirical test, a view eventually championed by Popper (1959) as his *falsifiability principle*. This modification finally admitted that theory terms could never be directly 'verified' empirically.

In responding to the fundamental dilemma, the logical empiricists attempted to deal with the problems identified with the logical positivists' strict separation of theory and observation terms via the use of C-rules. How to have an 'unreal' theory term explicitly defined via C-rules without having the theory term simply be the result of an observable measure of some sort? This would become an *operationalist's* treatment of theory – it is whatever is measured (Hempel, 1954). It created the 'theoreticians dilemma': (1) *If all theory terms can be explicitly defined by reduction to observation terms, then theory terms are unnecessary*; and (2) *If theory terms cannot be explicitly defined and related to observation terms they are surely unnecessary because they are meaningless* (Hempel, 1965: 186). Further, if theory terms are isomorphic to operational measures there is no possibility of using the theory to predict new phenomena, as yet unmeasured.

It is clear that the term 'positivism' is now obsolete among modern philosophers of science (de Regt, 1994). Nevertheless, many key ingredients of positivism still remain in good standing among scientific realists, such as: theory terms, observation terms, tangible observables and unobservables, auxiliary hypotheses, causal explanation, empirical reality, testability, incremental corroboration and falsification, and generalizable law-like statements. Though Suppe (1977) wrote the epitaph on positivism and relativism, a positivist legacy remains (McKelvey, 1999). The idea that theories can be unequivocally verified in search for a universal unequivocal 'Truth' is gone. The idea that 'correspondence rules' can unequivocally connect theory terms to observation terms is gone. The role of axioms as a basis of universal Truth absent empirical tests is negated. The importance of models and experiments is reaffirmed.

The fallacy of positivist economics

The evolutionary aspect of economics originates in attempts by Spencer (1898) and

Friedman (1953) to use Darwinian selectionist theory to justify why only rational firms survive. Samuelson (1947) and Friedman (1953) draw on the mathematics of classical physics, its First Law of Thermodynamics (the conservation of energy law), and the centrality of equilibrium, in attempting to turn economics into a predictive science (Mirowski, 1989). To get economics out of its equilibrium-centric stance, Nelson and Winter (1982) use Darwinian selectionist theory to introduce dynamics into economic 'Orthodoxy'. More recently, however, Salthe (1993), Rosenberg (1994), and Eldredge (1995) all recast Darwinian selectionist theory as an equilibrium-based theory as well. They conclude that the most significant dynamics in the bio- and econspheres are variances around equilibria in niches remaining stable for millions of years. While Darwinian selection is still important at the tail end of the order-creation process, the 'self-organization biologists' (Van de Vijver et al., 1998) see other natural forces surrounding the biosphere as causing the more significant changes in biological entities over the millennia. Self-organization biology enters the mix as an important additional component of bioeconomics.

Hinterberger (1994) critiques economic orthodoxy's reliance on the equilibrium assumption from a different perspective. In his view, a closer look at both competitive contexts and economic actors uncovers four forces working to disallow the equilibrium assumption:

1 Rapid changes in the competitive context of firms does not allow the kinds of extended equilibria seen in biology and classical physics;
2 There is more and more evidence that the future is best characterized by 'disorder, instability, diversity, disequilibrium, and nonlinearity' (p. 37);
3 Firms are likely to experience changing basins of attraction – that is, the effects of different equilibrium tendencies;
4 Agents coevolve to create higher-level structures that become the selection contexts for subsequent agent behaviours.

Hinterberger's critique comes from the perspective of complexity science. Also from this view, Arthur et al. (1997: 3–4; who draw from Holland, 1988) note that the following characteristics of economies counter the equilibrium assumption essential to predictive mathematics:

1 *'Dispersed Interaction'* – dispersed, possibly heterogeneous, agents active in parallel;
2 *'No Global Controller or Cause'* – coevolution of agent interactions;[3]
3 *'Many Levels of Organization'* – agents at lower levels create contexts at higher levels;
4 *'Continual Adaptation'* – agents revise their adaptive behaviour continually;
5 *'Perpetual Novelty'* – by changing in ways that allow them to depend on new resources, agents coevolve with resource changes to occupy new habitats; and
6 *'Out-of-Equilibrium Dynamics'* – economies operate 'far from equilibrium', meaning that economies are induced by the pressure of trade imbalances, individual to individual, firm to firm, country to country, etc.

After reviewing all the chapters, most of which rely on mathematical modelling, the editors ask, '… *In what way do equilibrium calculations provide insight into emergence?*' (p. 12; my italics). Most chapters miss the essential character of complex adaptive systems stylized in the bullets – heterogeneous agents in far-from-equilibrium systems.

In his book, *Dynamics of Markets: Econophysics and Finance*, McCauley (2004) observes that in physics a mathematical model is confirmed or not via empirical experiments; the math lives or dies depending on the experiments. In economics McCauley shows that *it is not so*; economists adhere to their math models whether or not they are empirically confirmed. In economics reliance on the math from equilibrium physics (Mirowski, 1989) amounts to a *faith-based would-be science*. I offer some specific quotes from McCauley's book in Table 6.1.

The lack of empirical confirmation of theories and their math formalizations is further confirmed by the quotes of

Table 6.1 Joseph McCauley's evaluation of theoretical economics – the math stuff

- 'The known mathematical laws of nature, the laws of physics, do not change. … Local invariances … can be reproduced by different observers independently …'. (p. 2)
- 'We know mathematical laws of nature that cannot be violated intentionally … are beyond the possibility of human invention, intervention, or convention'. (quoting Alvin Turing; p. 2)
- '… Notwithstanding the economists' failed attempt to make economics look like an exercise in calculus … in economics in contrast with physics, there exist no known inviolable mathematical laws of 'motion'/behavior. … Economic 'law', like any legislated law or social contract, can always be violated by willful people and groups'. (p. 3)
- 'Econometric models … are too complicated and based on too few good ideas and too many unknown parameters to be very useful'. (p. 6)
- 'The aim of this book is to make it clear to the reader that neo-classical theory, beloved of pure mathematicians, is a bad place to start in order to make new models of economic behavior'. (p. 6)

economists, no less – listed in Table 6.2 – who point to the total disjunction between econometrics and economists' beliefs in their theories. Economists claim that econometrics is a valid substitute for experiments (where the independent variable can be directly shown to cause the dependent variable – or not). This claim was refuted in a classic test by Lalonde (1986) of whether any of the best econometric models could replicate a real-world experiment.[4] *They couldn't*!

REALISM

From the positivist legacy a *model-centred evolutionary realist epistemology* has emerged. Elsewhere (McKelvey, 1999), I argue that model-centred *realism* accounts to the legacy of positivism and evolutionary realism accounts to the dynamics of science highlighted by relativism, all under the label *Campbellian Realism*. Campbell's view may be summarized into a tripartite framework that replaces the historical relativism of Kuhn (1962) and Feyerabend (1975) for the purpose of framing a dynamic realist epistemology. ***First***, much of the literature from Lorenz (1941) forward has focused on the selectionist evolution of the human brain, our cognitive capabilities, and our visual senses (Campbell, 1974); it concludes that these capabilities do indeed give us accurate information about the world we live in (reviewed by Azevedo, 1997).

Second, Campbell (1991) draws on the hermeneuticists' coherence theory in a selectionist fashion to argue that over time members of a scientific community (as a tribe) attach increased scientific validity to an entity as the meanings given to that entity increasingly cohere across members. This process is based on hermeneuticists' use of coherence theory to attach meaning to terms (Hendrickx, 1999). This is a version of the social constructionist process of knowledge validation that defines Bhaskar's (1975) use of transcendental idealism and the sociology of knowledge components in his scientific realist account. The coherentist approach selectively winnows out the worst of the theories and thus approaches a more probable truth.

Third, Campbell (1991) and Bhaskar (1975) combine scientific realism with semantic relativism. Nola (1988) separates relativism into three kinds:

1 'Ontological relativism is the view that what exists, whether it be ordinary objects, facts, the entities postulated in science, etc., exists only relative to some relativizer, whether that be a person, a theory or whatever' (1988: 11) – [*ontologically nihilistic*].
2 Epistemological relativisms may allege that (1) what is known or believed is relativized to individuals, cultures, or frameworks; (2) what is perceived is relative to some incommensurable

Table 6.2 Economists on the value of econometrics*

- 'No economic theory was ever abandoned because it was rejected by some empirical econometric test, nor was a clear cut decision between competing theories made in light of the evidence of such a test.' (Spanos, 1986: 660)
- 'Very little of what economists will tell you they know, and almost none of the content of the elementary text, has been discovered by running regressions. Regressions on government-collected data have been used mainly to bolster one theoretical argument over another. But the bolstering they provide is weak, inconclusive, and easily countered by someone else's regressions.' (Bergmann, 1987: 192)
- 'We don't genuinely take empirical work seriously in economics. It's not the source by which economists accumulate their opinions, by and large.' (Leamer in Hendry et al., 1990: 182)
- 'I invite the reader to try and identify a single instance in which a "deep structural parameter" has been estimated in a way that has affected the profession's beliefs … . (Summers, 1991: 130)
- 'No one really believes a scientific assertion in economics based on statistical significance.' (McCloskey, 1994: 358)
- 'Most allegedly empirical research in economics is unbelievable, uninteresting or both. It doesn't get down to the phenomena. It's satisfied to be publishable or clever. It's unbelievable unless you have to believe temporarily to get tenure.' (McCloskey, 1994: 359)
- 'In economics it takes a theory to kill a theory, facts can only dent a theorist's hide.' (Samuelson quoted in Card and Krueger, 1995: 355)

* Collected by Pierpaolo Andriani.

paradigm; (3) there is no general theory of scientific method, form of inquiry, rules of reasoning or evidence that has privileged status (1988: 16–18) – [*epistemologically nihilistic*].

3 Semantic relativism holds that truth and falsity are '… relativizable to a host of items from individuals to cultures and frameworks. What is relativized is variously sentences, statements, judgements or beliefs' (1988: 14) – [*semantically weak*].

Nola observes that Kuhn and Feyerabend espouse both semantic and epistemological relativism. Relativisms[5] familiar to social scientists range across all three kinds, that is, from ontological nihilism to semantic. Campbell clearly considers himself a semantic relativist in addition to being an ontological realist (Campbell and Paller, 1989). This produces an ontologically strong, relativist, dynamic epistemology. In this view the coherence process within a scientific community continually develops in the context of selectionist testing for ontological validity. The socially constructed coherence-enhanced theories of a scientific community are tested against real-world phenomena (the criterion variable against which semantic variances are eventually narrowed and resolved), with a winnowing out of the less ontologically correct theoretical entities. This process, consistent with the strong version of scientific realism proposed by de Regt (1994), does not guarantee error-free 'Truth' (Laudan, 1981), but it does move science in the direction of Popper's (1959) increased verisimilitude (truthlikeness).

Campbellian realism is crucial because elements of positivism and relativism still flourish in social science. Campbell's is an epistemology: (1) dealing with metaphysical terms, (2) objectivist empirical investigation, (3) recognition of socially constructed meanings of terms, and (4) a dynamic process by which a multiparadigm discipline usually reduces to fewer but more significant theories.

Campbell defines a critical, hypothetical, corrigible, scientific realist selectionist evolutionary epistemology as follows (McKelvey, 1999: 403):

1 A scientific realist postpositivist epistemology that maintains the goal of objectivity in science without excluding metaphysical terms and entities.

2 A selectionist evolutionary epistemology governing the winnowing out of less probable theories, terms, and beliefs in the search for increased verisimilitude may do so without the danger of systematically replacing metaphysical terms with operational terms.
3 A postrelativist epistemology that incorporates the dynamics of science without abandoning the goal of objectivity.
4 An objectivist selectionist evolutionary epistemology that includes as part of its path toward increased verisimilitude the inclusion of, but also the winnowing out of the more fallible, individual interpretations and social constructions of the meanings of theory terms comprising theories purporting to explain an objective external reality.

The epistemological directions of Campbellian realism have strong foundations in the scientific realist and evolutionary epistemology communities (see Azevedo, 1997). *The one singular advantage of realist method is its empirically based, self-correcting approach to the discovery of truth* (Holton, 1993). While philosophers never seem to agree exactly on anything, nevertheless, broad consensus does exist that these statements reflect what is best about current philosophy of science. To date evolutionary realism has amassed a considerable body of literature, as reviewed by Hooker (1987) and Azevedo (1997). Along with Campbell and Lawson's (1997) realist treatment of economics, Azevedo's book stands as a principal proponent of realist *social* science.

THE SEMANTIC CONCEPTION

In my development of Campbellian Realism (McKelvey, 1999) I show that model-centredness is a key element of scientific realism, but I do not develop the argument. In this section, I flesh out the development of a model-centred social science by defining the Semantic Conception. As Cartwright put it initially: 'The route from theory to reality is from theory to model, and then from model to phenomenological law' (1983: 4). The shift from Cartwright's earlier view of models as passive reflections of theory and data to '*models as autonomous agents*' mediating between theory and phenomena reaches fullest expression in Morgan and Morrison (2000), her protégés.

Models may be iconic or formal. Most management scholars live in the shadow of economists and economics departments dominated by economists trained in the context of theoretical (mathematical) economics. Because of the axiomatic justification of theoretical economics, I first discuss the axiomatic conception in epistemology and economists' dependence on it. Then I turn to the semantic conception, its rejection of the axiomatic definition of science, and its replacement programme.

The axiomatic syntactic tradition

Axioms are defined as self-evident truths comprised of primitive syntactical terms. Thus, in Newton's second law, $F = ma$: requires understanding mass (being hit by a large truck) and acceleration (being hit by a speeding Ferrari). And the three terms, force, mass, and acceleration cannot be decomposed into smaller physical entities defined by physicists – they are primitive terms this sense (Mirowski, 1989: 223). A formal syntactic language system starts with primitives – basic terms, definitions, and formation rules (e.g. specifying the correct structure of an equation) and syntax – in $F = ma$ the syntax includes F, m, a, = and × (implicit in the adjoining of ma). An axiomatic formal language system includes definitions of what is an axiom, the syntax, and transformation rules whereby other syntactical statements are deduced from the axioms. Finally, a formal language system also includes a set of rules governing the connection of the syntax to real phenomena by such things as measures, indicators, operational definitions, and correspondence rules all of which contribute to syntactic meaning.

Based on the work of Pareto, Cournot, Walras, and Bertrand, economics was already translating physicists' thermodynamics into a mathematicized economics by 1900. By the time logical positivism was established by the Vienna Circle *circa* 1907 (Hanfling, 1981), science and philosophy of science believed that a common axiomatic syntax underlay much of known science – it connected theories as far removed from each other as motion, heat, electromagnetism, and economics to a common set of primitives. Over the course of the twentieth century, as other sciences became more formalized, positivists took the view that any 'true' science ultimately reduced to this axiomatic syntax (Nagel, 1961; Hempel, 1965); this was the origin of the '*Unity of Science*' movement (Hanfling, 1981).

Now, the axiomatic requirement increasingly strikes many scientists as more straightjacket than paragon of good science. After quantum/relativity theories, even in physics Newtonian mechanics came to be seen as a study of an isolated idealized simplified physical world of point masses, pure vacuums, ideal gases, frictionless surfaces, linear one-way causal flows, and deterministic reductionism (Suppe, 1989: 65–68; Gell-Mann, 1994). But biology continued to be thought – by some – as amenable to axiomatic syntax even into the 1970s (Williams, 1970; Ruse, 1973). In fact, most formal theories in modern biology are not the result of axiomatic syntactic thinking. Biological phenomena do not reduce to axioms. For example, the Hardy–Weinberg 'law', the key axiom in the axiomatic treatments of Williams and Ruse is:

$$p = \frac{AA + 1/2Aa}{N}$$

where p is the gene frequency, A and a are two alleles or states of a gene, and N is the number of individuals. But instead of being a fundamental axiom of evolutionary theory, it is now held that this 'law', like all the rest of biological phenomena is a *result* of evolution, not a causal axiom (Beatty, 1981: 404–405).

The so-called axioms of economics also suffer from the same logical flaw as the Hardy–Weinberg law. Economic transactions appear to be represented by what Mirowski refers to as the 'heat axioms'. Thus, Mirowski shows that a utility gradient in Lagrangian form:

$$P = \text{grad } U = \left[\frac{\partial U}{\partial x}\ \frac{\partial U}{\partial x}\ \frac{\partial U}{\partial z}\right] = \left\{P_x, P_y, P_z\right\}$$

is of the same form as the basic expression of a force field gradient:

$$F = \text{grad } U = \left[\frac{\partial U}{\partial x}\ \frac{\partial U}{\partial y}\ \frac{\partial U}{\partial z}\right] = \left\{X, Y, Z\right\}$$

As Mirowski (1989: 30–33) shows, this expression derives from the axiom $F = ma$. Suppose that, analogous to the potential or kinetic energy of planetary motion defined by the root axiom $F = ma$, an individual's movement through commodity space (analogous to a rock moving through physical space) is $U = ip$ (where i = an individual, p = change in preference). *The problem is that Newton's axiom is part of the causal explanation of planetary motion, but the economists' axiom could be taken as the* result *of the evolution of a free market capitalist economy, not as its root cause*. This 'axiom' is not a self-evident expression that follows an axiomatic syntax common to all 'real' sciences. It is the result of how economists think an economy *ought* to behave, not how economic systems *actually* behave universally. Economists are notorious for letting *ought* dominate over *is* (Redman, 1991). Orthodox economic theory still is defined by axiomatic syntax (Hausman, 1992). It is pretty much a faith-based religion!

Essential elements of the semantic conception

Parallel to the fall of The Received View (Putnam's (1962) term combining logical positivism and logical empiricism) and its axiomatic conception, and starting with Beth's (1961) seminal work dating back to the Second World War, we see the emergence of the 'Semantic Conception of Theories' (Suppes, 1961; van Fraassen, 1970; Suppe, 1977, 1989; Beatty, 1987). Suppe (1989: 3) says, 'The Semantic Conception of Theories today probably is the philosophical analysis of the nature of theories most widely held among philosophers of science'. I present four key aspects:

From axioms to phase-spaces

Following Suppe, I will use *phase-space* instead of Lloyd and Thompson's state-space or Suppes' set-theory. A phase-space is defined as a space enveloping the full range of each dimension used to describe an entity. Thus, one might have a regression model in which variables such as size (employees), gross sales, capitalization, production capacity, age, and performance define each firm in an industry and each variable might range from near zero to whatever number defines the upper limit on each dimension. These dimensions form the axes of an *n*-dimensional Cartesian phase-space. Phase-spaces are defined by their dimensions and by all possible configurations across time as well. They may be defined with or without identifying underlying axioms – the formalized statements of the theory are not defined by how well they trace back to the axioms but rather by how well they define phase-spaces across various state transitions. *In the semantic conception, the quality of a science is measured by how well it explains the dynamics of phase-spaces – not by reduction back to axioms.*

Isolated idealized structures

Semantic conception epistemologists observe that scientific theories never represent nor explain the full complexity of some phenomenon. A theory may *claim* to provide a generalized description of the target phenomena, say, the behaviour of a firm, but no theory ever includes so many variables and statements that it effectively accomplishes this. A theory (1) 'does not attempt to describe all aspects of the phenomena in its intended scope; rather it abstracts certain parameters from the phenomena and attempts to describe the phenomena in terms of just these abstracted parameters' (Suppe, 1977: 223); (2) assumes that the phenomena behave according to the selected parameters included in the theory; and (3) is typically specified in terms of its several parameters with the full knowledge that no empirical study or experiment could successfully and completely control all the complexities that might affect the designated parameters. Suppe (1977: 223–224) says theories invariably explain *isolated idealized systems* (his terms). And most importantly, 'if the theory is adequate it will provide an accurate characterization of what the phenomenon *would have been* had it been an isolated system …'. Using her mapping metaphor, Azevedo (1997) explains that no map ever attempts to depict the full complexity of the target area – it might focus only on rivers, roads, geographic contours, arable land, or minerals, and so forth – seeking instead to satisfy the specific interests of the map maker and its potential users. Similarly for a theory. A theory usually predicts the progression of the idealized phase-space over time, predicting shifts from one abstraction to another under the assumed idealized conditions. Needless to say, the foregoing equates to Gell-Mann's 'effective complexity'.

Model-centred science and bifurcated adequacy tests

Models comprise the core of the semantic conception. In the *axiomatic conception*: (1) Theory is developed from its axiomatic base; (2) Semantic interpretation is added to make it meaningful in, say, physics, thermodynamics, or economics; (3) Theory is used to make and test predictions about the phenomena; and (4) Theory is defined as empirically and ontologically adequate if it both reduces to the axioms and is instrumentally reliable in predicting empirical results. In the typical *social science approach*: (1) Theory is induced after an investigator has gained an appreciation of some aspect of social behaviour;

(2) An iconic model is often added to give a pictorial (box-&-arrow) view of the interrelation of the variables, show hypothesized path coefficients, or possibly a regression model is formulated; (3) The model develops in parallel with the theory as the latter is tested for empirical adequacy by seeing whether effects predicted by the theory can be discovered in the real-world. In the *semantic conception*: (1) Theory, model, and phenomena are viewed as independent entities; (2) Science is bifurcated into two not-unrelated activities, analytical and ontological adequacy. My view of models as centred between theory and phenomena sets them up as autonomous agents, consistent with the various authors in Morgan and Morrison (2000). Consequently, they have two bases of validity:

- ***Analytical Adequacy*** focuses on the theory–model link. It is important to emphasize that in the semantic conception 'theory' is always expressed via a model. 'Theory' does not attempt to use its 'If *A*, then *B*' epistemology to explain '*real-world*' behaviour. It only explains '*model*' behaviour. It does its testing in the isolated idealized world of the model. A mathematical or computational model (see Prietula; Tracy; Vidgen and Bull; all this volume) is used to structure up aspects of interest *within* the full complexity of the real-world phenomena and defined as *'within the scope'* of the theory – which is to say it has to meet the standards of Gell-Mann's *effective complexity*. Thus, a model would not attempt to portray all aspects of, say, school systems – only those within the scope of the theory being developed.
- ***Ontological Adequacy*** focuses on the model–phenomena link. Developing a model's ontological adequacy runs parallel with improving the theory–model relationship. How well does the model *represent* real-world phenomena? *Is it effectively complex*? How well does an idealized wind-tunnel model of an airplane wing represent the behaviour of a full sized wing in a storm? How well does a drug shown to work on 'idealized' lab rats work on people of different ages, weights, and genetic variances? If each dimension in the model – called model-substructures – adequately represents an equivalent behavioural effect in the real world, the model is deemed ontologically adequate (McKelvey, 2001).

Theories as families of models

A difficulty encountered with the axiomatic conception is the belief that *only one* theory (or model) concept should build from the underlying axioms. In this sense, only one model can 'truly' represent reality in a rigorous science. Given this, a discipline such as evolutionary biology fails as a science. Instead of a single axiomatically rooted theory, as proposed by Williams (1970) and defended by Rosenberg (1985), evolutionary theory is a *family of theories* including theories explaining the processes of (1) variation; (2) natural selection; (3) heredity; and (4) a taxonomic theory of species (Thompson, 1989: Ch. 1). Even in physics, the theory of light is still represented by two models: wave and particle. Since the semantic conception does not require axiomatic reduction, it tolerates multiple theories and models. Thus, 'truth' is not defined in terms of reduction to a single model. Set-theoretical, mathematical, and computational models are considered equal contenders to more formally represent real-world phenomena. In physics both wave and particle models are accepted because they both produce highly reliable predictions. In evolutionary theory there is no single 'theory' of evolution. In fact, there are even lesser families of theories (multiple models) *within* the main families. All social sciences also consist of various families of theories, each having families of competing models within it.

EXTENDING REALISM TO GELL-MANN'S SECOND REGULARITY

Translating chaos into new regularities to be explained

Gell-Mann (2002) distinguishes between two fundamentally different '*regularities*' – what Bhaskar (1975) calls 'underlying generative processes'. As I noted earlier, Gell-Mann sees 'effective complexity' as '*regularities*' or 'schemas' found or judged to be useful. They appear as equations in physics, genotypes in biology, laws and traditions in social science, and business best practices in management or organization science. What is new is Gell-Mann's recognition of a new scalability-derived regularity. He defines two regularities: (1) the *old* simplicity of reductionism, equations, linearity, and predictions of classical physics; and (2) the *new* simplicity of tiny initiating events – what I call '*butterfly-events*' (based on Lorenz, 1972) – that initiate causal dynamics leading to nonlinearity, similar causal dynamics at multiple levels, power laws, and scale-free theory – what Gell-Mann (2002) calls historical frozen accidents. They are:

1 ***Reductionist law-like regularities***: The reductionist causal processes of normal science, which stem predominantly from independent-additive causal processes that are predictable and easily represented by equations (2002: 19) – the data and information much preferred in classical physics and neoclassical economics.
2 ***Multilevel scale-free regularities***: Outcomes over time that stem from connectivity and interactive multiplicative causal processes; they are set off by the random occurrence of tiny initiating events that are compounded by positive feedback effects over time; they may have lasting effects and become the 'frozen accidents' of history (2002: 20).

The *first* regularities have been the subject of science and philosophy of science and within the latter, positivism and scientific realism, which I extend to Campbellian realism, all of which are reframed by the Semantic Conception. These are the equilibrium-trending regularities that economists and thence management and organizational researchers have presumed could be lifted over from physics – the science of dead things – to the sciences of living things, particularly neoclassical economics. Where probability substituted for exact physics, Gaussian statistics became the order of the day; and still is.

The *second* regularities result from the effects of 'tiny initiating events' (what Holland (2002: 29) calls 'small inexpensive inputs' or 'lever point phenomena') – my '*butterfly-events*'. Lots of them occurring in a short time frame can create all of the bifurcation points giving rise to chaos and deterministic chaos theory (Gleick, 1987; Guastello, 1995). The butterfly-events of chaotic histories are never repeated, are not predictable, and can produce significant nonlinear outcomes that may become extreme events. Consequently, descriptions of these systems are at best problematic and easily outside the explanatory/scientific traditions of normal science. The underlying causes are self-organization and emergence – the core concerns of the Santa Fe Institute (SFI) (see for example: Cowan et al., 1994; Holland, 1995; Arthur et al., 1997).

SFI emphasizes the spontaneous *co*evolution of agents in complex adaptive systems.[6] Agents restructure themselves continuously, leading to new forms of emergent order consisting of patterns of evolved agent attributes and hierarchical structures displaying both upward and downward causal influences. Bak (1996) extends this treatment in his discovery of '*self-organized criticality*', a process in which butterfly-events can lead to complexity cascades of avalanche proportions best described as an inverse power law (PL).[7] I show how a Pareto distribution turns into an inverse PL when plotted on double-log scales in Figure 6.1. The signature elements are self-organization, emergence and nonlinearity. Kauffman's (1993) '*spontaneous order creation*' begins when three elements are present: (1) heterogeneous agents; (2) connections among them; and (3) motives to connect so as to improve fitness (better performance, learning, innovation, etc.). Remove any one element and nothing happens. According to Holland (2002) we recognize emergent phenomena as *multiple level hierarchies*, *bottom-up and top-down causal effects*, and *nonlinearities*. Gell-Mann (2002) concludes by noting that when butterfly-events spiral up such that their effects appear at multiple levels and are magnified, we see self-similarity, scalability, and PLs. Scalability, especially, applies to all living systems (Gell-Mann, 2002).

Seldom in the literature have scientific realists applied their epistemological views to butterfly events and consequences – an exception is *Worldviews, Science and Us: Philosophy and Complexity* (Gershenson et al., 2007). Underlying most PLs is a causal dynamic explained via scale-free theories. Each theory points to a single generative cause to explain the dynamics at each of however many levels at which the scalability effect applies. Whereas tradition rests on the idea that lower-level dynamics can explain and predict higher-level phenomena and simplicity comes in the form of (usually) linear mathematical equations – i.e. reductionism (Gell-Mann, 2002), scale-free theories point to the same causes operating at multiple levels – the 'simplicity' is one theory explaining dynamics at multiple levels. Andriani and McKelvey (2009) apply fifteen of these scale-free theories to organizations.

Explaining butterfly regularities via scale-free theories

Many complex systems tend to be '*self-similar*' across levels. That is, the same dynamics drive order-creation behaviours at multiple levels (West et al., 1997). These processes are called '*scaling laws*' because they represent dynamics appearing similarly at many orders of magnitude (Zipf, 1949). Scalability results from what Mandelbrot (1982) calls '*fractal geometry*'. Fractals often show Pareto distributions and are signified by PLs. Researchers find PLs in intrafirm decisions, consumer sales, salaries, size of firms, movie profits, director interlocks, biotech networks, and industrial districts, for example – Andriani and McKelvey (2007, 2009) assemble studies about ~140 PLs. They are mostly explained by scale-free theories. They (2009) also identify 15 scale-free theories applying to organizations. From the foregoing, two new complexity thrusts are identifiable.

First, roughly one-third of complexity science theory is missing in organizational and managerial applications to date, i.e. the econophysics phase – PLs and the underlying fractals, scalability, and scale-free theory. Organizations are multilevel phenomena. Almost by definition then, we can take PL signatures as the best evidence we have that emergence dynamics are operating at multiple organizational levels. We know for sure

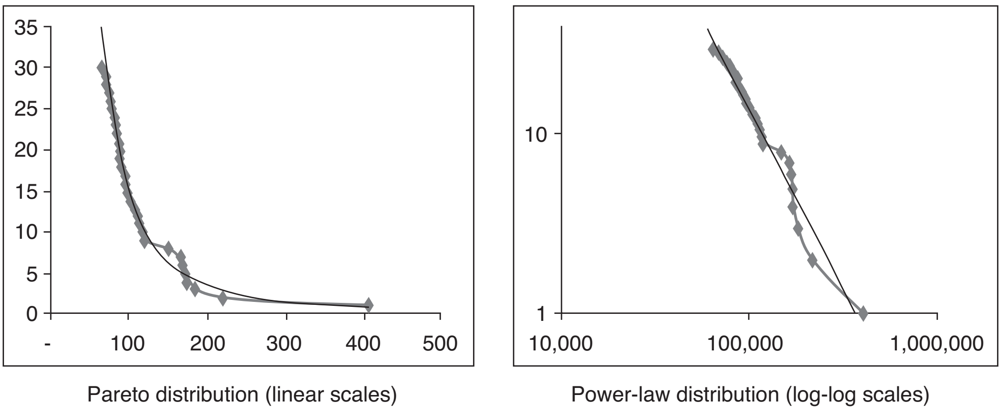

Figure 6.1 Pareto distribution reformed into a power-law distribution

Plots from Glaser (2009). They show the rank/frequency of the 30 largest software firms by market capitalization. The power-law distribution has a 0.97 correlation with the straight line that PLs apply at the industry level (Stanley et al., 1996; Axtell, 2001; Glaser, 2009). If PLs are not evident in a particular firm, we can conclude only that '*emergence*', if it exists at all, is not *multi*level. Building from the interacting food-web literature (Pimm, 1982; Solé et al., 2001; McKelvey et al., 2011), we can also conclude that, absent the PL signature, a firm's emergence dynamics are not capable of keeping it competitive with its changing competitors, suppliers, and customers. Thus, if emergence produces scale-free dynamics, but PLs are not evident, then whatever emergence actually exists is pretty much competitively useless. The bottom line is that PLs are significant indicators of crucially important managerial and organizational dynamics (Andriani and McKelvey, this volume). This puts the practical relevance of current empirical research in an especially bad light. No wonder people say b-schools (and their research) are increasingly irrelevant (Pfeffer and Fong, 2002; Bennis and O'Toole, 2005; Ghoshal, 2005).

Second, organization change and entrepreneurship researchers should be especially interested in scale-free dynamics and related theories. Who more than entrepreneurs wouldn't like to let loose scale-free dynamics in their firms? Think of how many small entrepreneurial ventures stay that way simply because the emergent growth dynamics they had at the one- or two-level size failed to scale up as levels increased. Think how many large organizations show failing intrapreneurship for the same reason – the hundreds of 'butterfly-ideas' never become meaningful butterfly-events, never produce butterfly-effects, and never spiral into multilevel scale-free causal dynamics producing PL signatures. We now have recent research showing that PLs do indeed indicate changing firms (Dahui et al., 2006; Ishikawa, 2006), transition economies (Podobnik et al., 2006), and the UK's broken industrial economy (McKelvey, 2011).

Extant complexity theory applied to organizations and management is silent on both the foregoing points. I think the most important move we could take is to learn how, and then more aggressively, apply scale-free complexity theory to organization change, OD, and entrepreneurship/intrapreneurship. Teaching and preaching complexity theory is useless in our organizational world absent scale-free theory. These points are further elaborated in chapters by Andriani and McKelvey, and Boisot and McKelvey (this volume).

CONCLUSION

Complexity Science Epistemology (CSE) cannot gain ontological and epistemological legitimacy and consequent truth claims by mirroring classical physics, which is to say mirroring its:

1. Lower-bound homogeneity assumption (e.g. all H_2O molecules, as agents, may be treated as similar);
2. Entropy-production based equilibrium-centred math modelling syntactic-equation-based practices;
3. Reductionism and prediction based on instrumental variables (prediction-useful as opposed to explanation-useful); and
4. Reliance on axiomatically-based syntactically-correct math expressions/proofs as opposed to semantically-relevant effectively-complex models.

Instead, CSE has to reflect an ontological jump from Gell-Mann's First Regularities to his Second Regularities. This means CSE's truth claims require developing the following – mostly new – epistemologies:

First: CSE shifts *from* ontologies, models, and epistemologies presumed to be based on constituent elements that are independent and combine additively *to* ontologies and agent-based computational models in which constituent elements (the agents) show connectivity and can interact so as to produce multiplicative, nonlinear outcomes, which give rise to Gell-Mann's scalability-based Second Regularities. Complexity science, centred around emergent order-creation and complexity from the interactions of autonomous heterogeneous agents, has developed an *agent-based model-centred epistemology* that parallels the social and language connectivities and individual-research-based truth claims emphasized in postmodernism and poststructuralism (Cilliers, 1998).

Second: CSE retains reliance on Campbellian realism and evolutionary epistemology: Campbellian realism – coupled with the Semantic Conception and evolutionary epistemology – bases scientific legitimacy on (a) theories aimed at explaining (and not just predicting) transcendental causal mechanisms or processes (i.e. including variables above and below the human senses); (b) the insertion of effectively-complex models as an essential element of sound epistemology; and (c) the use of changing real-world phenomena as the criterion variable leading to: (i) an evolutionary winnowing out of less plausible social constructions and individual interpretations; as well as (ii) constant updating of truth-claims.

Third: CSE recognizes four basic ontological forms stemming from the Second Regularity – which results in Pareto and PL distributed phenomena. Figure 6.2 depicts a stylized PL distribution. Within this figure we see four kinds of ontologies, each calling for different epistemologies. Since these ontologies are described in more detail by Andriani and McKelvey (this volume), I just describe them briefly here:

1 ***Extreme outcomes:*** At the lower right we have what Siggelkow (2007) and Andriani and McKelvey call 'talking pigs' – really strange, unusual, one-of-a-kind outcomes: a once-a-century #9 earthquake; Walmart and Microsoft (the largest firms in the world in their industries), the Challenger disaster, the Bay of Pigs confrontation between Russia and the U.S., etc. For this ontology, CSE truth claims should come from epistemologies such as hermeneutics and coherence theory (Campbell, 1991; Hendrickx, 1999), multimethod research (Jick, 1979) and abductive reasoning (Peirce, 1935; Hanson, 1958; Paavola, 2004; see also Boisot and McKelvey, this volume).

2 ***Normal distributions:*** At the upper left we see the PL representation of the opposite Pareto long tail. This is where we usually see high enough frequencies of some phenomena that Gaussian statistics applies. While there is only one Walmart at the lower-right, there are millions of Ma&Pa stores at the upper left. CSE truth claims based on Campbellian realism and evolutionary epistemology fit this ontology very well.

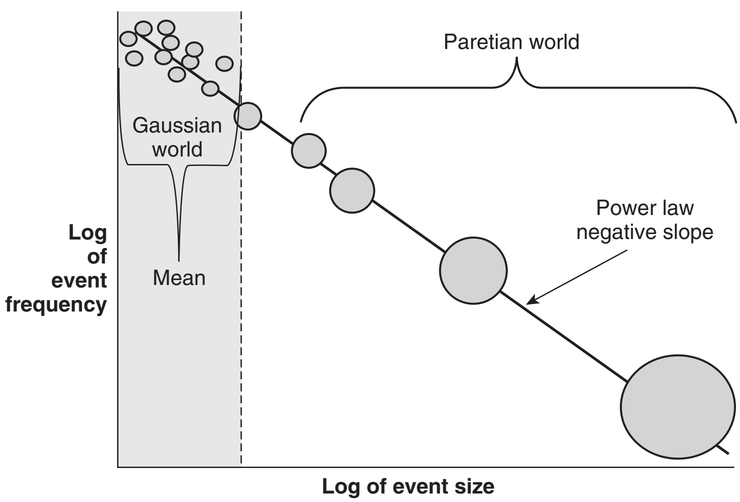

Figure 6.2 Stylized power-law distribution

3 ***Anderson's long tail:*** Also at the upper left, Anderson (2006) describes a variety of phenomena that appear in micro-niches, Amazon book sales being a good example; it can supply one weird book to one idiosyncratic customer and still make a profit from doing so. This perspective has been validated by Brynjolfsson et al. (2006). This epistemology is not well developed.

4 ***Horizontal scalability:*** Going horizontally in Figure 6.2, the ontology is that of, for example, Southwest Airlines going from a start-up regional airline in Texas to now being worth more than all the rest of the US airlines combined (Maxon, 2008). Sam Walton's initial Ma&Pa-type store grew from very small to extremely large; most stores didn't. Here the ontology is one of tiny initiating events – sometimes – leading to extreme outcomes. Truth claims here rest on epistemologies yet to be developed since Pareto distributions have been mostly ignored by statisticians and researchers for over a century. Andriani and McKelvey (this volume) describe the ontology in more detail. As power law science develops, a relevant CSE epistemology will presumably follow.

Model-centred science is a two edged sword. On the one hand, formalized models are reaffirmed as a critical element in the already legitimate sciences and receive added legitimacy from the Semantic Conception in philosophy of science. On the other, the more we learn about *models as autonomous agents* – that offer a third influence on the course of science, in addition to mirroring theory and/or data – the more we see the problematic moulding effects math models have had on social science. In short, math models are mostly inconsistent with living phenomena. A model-centred epistemology based on agent-based computational models (see Prietula; Tracy; Vidgen and Bull; all this volume) (and some math) is required for efficacious management research and practitioner advice giving. It is only a beginning, but I note that CSE truth claims call for radically different ontologies, models, and epistemologies calling for new developments in scientific realism.

NOTES

1 Originally: O. Neurath, with R. Carnap and H. Hahn, *Die Wissenschaftliche Weltauffassung, Der Wiener Kreis*. Wien: Artur Wolf 1929. [A pamphlet reprinted and translated in M. Neurath and R.S. Cohen (eds) *Empiricism and Sociology*, Dordrecht, The Netherlands: Reidel, 1973: 301–318.]

2 The paper is reprinted in Boyd, Gasper, and Trout as 'Positivism and Realism' (1991: 37–55).

3 While there is no global controller in bee and ant colonies, firms have CEOs earning $$millions to be in charge. Hence, complexity science applied to organization and management has to deal with varying amounts of global control.

4 Lalonde's test includes James Heckman's two-stage method, for which he (Heckman) won the Nobel Prize.

5 Includes ontologically and/or epistemologically nihilistic subjectivist *postpositivisms* such as ethnomethodology, historicism, radical humanism, phenomenology, semioticism, literary explicationism, hermeneuticism, critical theory, and postmodernism, all of which are 'post' positivist and in which subjective and cultural forces dominate ontological reality.

6 Since the SFI complexity approach is discussed elsewhere in this volume, I only touch on it here.

7 'A Pareto rank/frequency distribution plotted in terms of double-log scales appears as a PL distribution – an inverse sloping straight line. … PLs often take the form of rank/size expressions such as $F \sim N^{-\beta}$, where F is frequency, N is rank (the variable) and β, the exponent, is constant. In exponential functions, e.g. $p(y) \sim e^{(ax)}$, the exponent is the variable and e (Euler number) is constant (quoted from Andriani and McKelvey, this volume).

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7

Exploring Organizational Effectiveness: The Value of Complex Realism as a Frame of Reference and Systematic Comparison as a Method

David Byrne

Almost everything Byrne knows about organizations in any formal sense, as opposed to a considerable amount of knowledge generated by lived experience working in organizational settings of rather different kinds,[1] comes from Mouzelis' *Organization and Bureaucracy* (1967) which he read as a graduate student just about 40 years ago. One key point stuck with him which Mouzelis derived from Herbert Simon. Organizations were about achieving objectives. We can add to that that they do so not by maximizing, but by satisficing – just one of Simon's great achievements was to recognize the limitations of human capacity in relation to available information and the necessity of seeking to seek to achieve adequacy rather than optimal outcomes. We are going to push this a bit or perhaps even a great deal further. Simon's background was in mathematical economics and operational research and very much informed by the mathematical techniques involved in the development of Physics. There is a way in which that kind of mathematics has built into it a version of the world in which all is mutable by degree. In other words optimization is definable by maxima in terms of some sort of multi-dimensional state space where all the dimensions of the state space can be measured in ways which assigns the full set of properties of number to the variables being measured.

Well organizations are complex systems and complex systems are in general not mutable by degree but mutable in relation to kind – change is not incremental but qualitative. The level of measurement which is appropriate in dealing with them is not continuous/ratio scale but nominal/categorical. The whole idea of phase shift which is central to an understanding of change in complex systems necessarily involves an understanding of measurement of change in categorical terms.[2] In relation to organizations whose outputs can be defined in financial terms, this reality can be obscured by the reality of money as a continuous variable. Rates of return on capital employed and changes in share value certainly are measurable in ratio scale terms. However, even for commercial organizations significant change is often qualitative. Bankruptcy/failure certainly is a qualitative change. Changes in form are usually nonlinear and involve radical shifts in size and complexity of functions. In any event the focus in this chapter is going to be on organizations whose purposes are not measurable in financial terms, although of course financial aspects are very important for them. In effect all devalorized organizations, i.e. organizations where the fundamental objective is not the accumulation of capital and enhancement of the rate of return on capital, should be considered as having objectives where change in effectiveness of outcome must be understood in categorical terms. Those categories may very well be ordered in terms of normative conceptions of their desirability, but ordered categories remain categories. Ragin and Rihoux put this very well in relation to a review of the technique – Qualitative Comparative Analysis (QCA) – which will be presented as a way of understanding causality in relation to outcome in complex systems in this chapter:

> … policy researchers, especially those concerned with social as opposed to economic policy, are often more interested in different kinds of cases and their different fates than they are in the extent of the net causal effect of a variable across a large encompassing population of observations. After all, a common goal of social policy is to make decisive interventions, not to move average levels or rates up or down by some miniscule fraction. (Rihoux and Ragin, 2004: 18)

So we want to develop an account of the nature of significant organization change in terms of qualitative transformation and propose that systematic comparison provides a means by which the complex and multiple causal processes which can generate particular desired states in relation to change can be understood, and being understood, managed.

In order to do this we need to spell out an ontological position – be absolutely explicit about the nature of the elements with which we are dealing and about the context of those elements. Most of the preceding discussion has been ontological. In particular by specifying organizations as complex systems and asserting that changes in those systems has to be understood in qualitative/categorical terms, we have already committed to the notion that what matters for us is complexity rather than simplicity. We want to add to that the implications of the realist understanding of the character of the world and of our processes of production of knowledge about that world as this has been outlined by Reed and Harvey (1992) who argue for a synthesis of the general description of complex systems in complexity theory, and especially for the significance of emergence and the nature of radical transformation which is part of the potential of complex systems, with critical realism after Bhaskar (see Archer et al., 1998) and in particular both the layered theory of reality and how we know it which informs that position. We can think of generative mechanisms, Bhaskar's real, as the potential causal drivers of complex systems – equivalent in complexity terms to control parameters, the actual expression of these in what Bhaskar calls the actual as the state of complex systems, and our description of complex systems as Bhaskar's empirical.

Pawson and Tilley's (1997) formulation of the realist causal principle, as slightly modified by Byrne (2002) serves as a summary of the understanding of causality which we can consider to inform complex realism:

Mechanism & Context => Outcome

In words, generative mechanism in interaction with context (hence the & rather than + sign as the latter implies simple additivity) generates directionally (hence => rather than = because = always implies reversibility and complex causality is directional) outcome.

The complex realist position will be developed in relation to the exploration of causality in complex systems, with that causality understood as almost always being contingent, complex and multiple. By contingent we mean here that causality is always dependent on context, on the surrounding environment in which any complex system is embedded. In other words causality is local. By complex we mean that causality in complex systems seldom depends on the operation of any single specific cause but rather is a consequence of the interaction of multiple causal factors, which may themselves be 'interactions' rather than discrete variate characteristics or interventions. By multiple we mean simply (!) that complex causality may operate in different ways. In other words the same outcome may be generated by different causal combinations.

This ontological specification is necessary because it predicates a very different understanding of causality from that which underpins traditional approaches to exploring cause, and in particular to the specific aetiology which lies behind randomized controlled trials. At a time when the Campbell collaboration (see http://www.campbellcollaboration.org/) whilst not quite following the Cochrane Collaboration's absolute privileging of the RCT (see Shadish and Myers, 2004), in their wholly admirable pursuit of evidence as to effectiveness of social interventions, nonetheless still see randomization and control as an ideal, it is really rather important to apply a complexity perspective to our understanding of how to find out 'what works'.

Teisman et al. (2009) develop these kind of arguments in specific relation to *Managing Complex Governance Systems.* They remark:

> Our starting point is the empirical observation that governance systems and networks are often in states of change which make them difficult to analyze, let alone manage. Stability of governance systems seems to be the exception rather than the rule. Furthermore, any changes that do take place are often capricious. Processes seem to unfold in unique and non-replicable ways, making it difficult to learn from successes and failures and to develop general theories. … This then begs the question of how to develop knowledge about such an elusive subject of research. An attempt is made here by starting from a complexity theory perspective, with the assumption that the interactions in governance networks are complex: the outcomes of interactions between parties do not only result from the intentions and actions of these two parties, but also from interferences from the context in which the interaction takes place and the emerging results of such interactions. This means that the output and outcomes of the same interaction can differ in different places and at different times. A governance approach or organizational arrangement applied in two different contexts can result in very different outcomes. (2009: 2)

In other words finding out 'what works' for complex governance systems or indeed any sort of complex organizational system, is not a straightforward business. This chapter will develop this argument illustrating how a complex realism frame of reference can help us to develop a systematic comparative case based approach to understanding the different 'whats' that work. It will use the example how we can explore 'Spearhead Areas' (local authority areas with high deprivation and poor health outcomes) in relation to what complex sets of control parameters/complex causes (for us these terms are synonymous) generate outcomes in relation to specific sets of health targets. We will show how the techniques of Qualitative Comparative Analysis (QCA) (see Ragin, 1987) can provide the basis of an exploratory approach to the whole operation of complex organizations in relation to the achievement of objectives. In doing so it develops primarily the technical side of the argument advanced by Buijs et al. that: '… it may be possible to make a systematic comparison across systems as a way of exploring situated complexity (complexity in which we have to take account of the specific character of a particular complex system in context)'. (2009: 37).

The proposal to work through cases is in itself not radical. After all the case study has been a or even the crucial tool of organizational analysis for a long time. However, we have to think carefully about the content and form of case study work and recognize that what we need above all else to handle an understanding of causality through case based approaches is comparison. In other words we need to get beyond the unique description of the ideographic account of the individual case but not work in terms of the establishment of nomothetic universal rules through some ersatz version of the experimental approach. Here the foreword to the third edition of Yin's classic account of *Case Study Research* (2003) written by the Donald Campbell for whom the Campbell collaboration is named makes two interesting and apposite points:

> More and more I have come to the conclusion that the core of the scientific method is not experimentation per se but rather the strategy connoted by the phrase 'plausible rival hypotheses'. This strategy may start its puzzle solving with evidence, or it may start with hypotheses. Rather than presenting this hypothesis or evidence in the context independent manner of positivist confirmation (or even of post-positivist corroboration), it is presented instead in extended networks of implications that (although never complete) are nonetheless crucial to its scientific evaluation. (2003: ix)
>
> … in addition to the quantitative and quasi-experimental case study approach that Yin teaches, our social science methodological armamentarium also needs a humanistic validity-seeking case study methodology that, although making no use of quantification or test of significance, would still work on the same questions and share the same goals of knowledge. (2003: ix–x)

Actually QCA seems to us to offer an approach which rather than focusing on plausible rival 'hypotheses' (although we prefer the term model to hypothesis), allows for multiple alternative accounts of how causes work in specific contexts which are alternative without being rival. In other words the adjective rival is wholly appropriate in relation to the word hypothesis since that term implies absolutely a single account of how causes work in a specific instance. In contrast the term 'model' allows for multiple and different causal processes. Also the processes of QCA actually combined the kind of qualitative methodology which Campbell calls for in the second of the above quotations with a quantitative process of clarification and specification through the construction of truth tables.

George and Bennett (2005) have a take on case studies which helps us here. They identify three components to case based qualitative work which is concerned with understanding causality – with helping us to work out in our language 'what works'. These are:

- Cross case comparison
- Congruence testing
- Process tracing

In some ways these interesting commentators remain trapped in a variable centred understanding of causation. This is particularly the case in relation to their discussion of congruence testing (see Chapter 9 of their book) which in effect involves advance specification through a hypothesis of the relationship between an independent variable and an outcome and the examination of cases to see if this relationship holds up, with of course the caveat that even the observation of such an association may lead us into the trap of the fallacy of affirming the consequent. In contrast process tracing which requires detailed engagement with the actual historical development of specific cases, results in the development of causal narratives. They quote Hall citing George himself:

> … process-tracing is a methodology well-suited to testing theories in a world marked by multiple interaction effects, where it is difficult to explain outcomes in terms of two or three independent variables – precisely the world that more and more social scientists believe we confront. (2000: 14; quoted in George and Bennett, 2005: 206)

The point about QCA is that it enables us to move from the detailed narrative of process tracing through specification of attributes which characterize multiple cases into the construction of configurations which represent multiple combinations of attributes leading or not leading to outcomes. Indeed Byrne (2009) shows how we might in an exploratory fashion start actually with an array of attributes for large *N* sets of cases and then explore the relationship of these with outcomes, prior to detailed qualitative exploration of processes in relation in particular to configurations of attributes which generated different outcomes. In other words we can do what qualitative comparison always suggest – find things which seem the same but lead to different outcomes, and then go into the cases further to find what else is different about them. To cross over into the technical language of complexity theory itself, we are actually interested in the differing trajectories of near neighbours in the state space. Systematic cross case comparison lets us explore trajectories which differ going forward albeit that the state from similar locations in the position of cases/systems in the ensemble of systems as located in the possible state space.

Cross case comparison is of course the fundamental basis of the comparative method. In all case comparison, particularly when we are dealing with case comparisons across large *N* data sets, a central theme is the construction of typologies. We might do this in an exploratory fashion using numerical taxonomy techniques, in particular cluster analyses. A realist complexity account actually suggests that classification deployed in relation to specific related attribute sets generates types which represent complex sub-sets of the whole complex systems, and may thus be considered to constitute descriptions of control parameters for those systems. This idea is developed in Byrne (2002) but an example will illustrate. If, for example, we are exploring differences in outcome across English secondary schools, organizations which certainly do constitute complex systems, we might well have data describing the pupils coming into the school in terms of initial ability as measured on tests, deprivation usually measured in terms of eligibility for free school meals, ethnicity and particularly the use of a language other than English in the home, and special needs being either or both cognitive and physical disabilities. Aggregate data about pupil cohorts can be clustered to yield input types for those schools and we would be hard put to argue that these factors *in interaction* have no determinant effect on outcome. Constructing clusters generates typologies which embody those interactions and which constitute variate traces of the systems under consideration. It is really rather important to emphasize that the foregoing is still to some extent trapped in the language of variables. The measures from which we construct clusters for cases do not exist outside those cases and/or the environment of those cases. The measures themselves are not 'real' nor are they, as factor analysis would have it, traces of some hidden real underlying variables with causal powers independent of the case/environment complex. They are variate traces and are best thought of as measured attributes. What is real – and here we are very close to Bhaskar – is the complex and fuzzy/fluid generative mechanism sets – the plural is important here. These exist only in action – only when they work. As Edward Thompson said of class we are dealing not with labels which exist outside people and situations, but with the noise, sound and smoke of things in action.

Of course this kind of clustering is a very useful technique of data reduction, and this is particularly valuable when we are dealing with dichotomous QCA in which attributes and outcomes have two values – 1 if present and 0 if absent. The number of possible configurations for *N* binary attributes is 2^N and that can become very large for large *N*. However, there is more to the approach. This can be illustrated by comparing classification of cases through cluster analyses with factor analyses which focus on variables. The whole logic of factor analysis remains trapped in the idea of causal determination as being due to variables external to cases. In that style we use matrix algebra to identify these factors from large numbers of variables measured for cases which are considered to be traces of these real underlying variables we call factors. In contrast in cluster analysis we identify sets of cases which have membership of multiple categories which in the language of complexity we might equate with attractor locations for those cases in a multi-dimensional state space.

One writer who has addressed the role of QCA in relation to organizational analysis is Peer Fiss who explicates configurations in a helpful fashion:

> What emerges, then, is a picture of configurations as embedded in space and time and involving varying levels of complexity, dynamism and analysis. Simple configurations may involve only a few and linear interdependencies. In contrast, complex configurations may involve multiple interdependencies that are furthermore characterized by interactions such as complementarity or substitution effects leading to synergies and trade-offs between the different elements. Furthermore, configurations need not be static, but may be dynamically changing, suggesting that organizations follow dynamic constellations that change over their life cycles. … Finally, configurations may be cutting across several levels of analysis. For example, organizational configurations may involve elements at the organizational, intra-organizational, and supra-organizational level. (2009: 429–430)

Let us apply this to considering outcomes in relation to real organizational entities. I want to pick as an example the performance of a subset of English Primary Care Trusts in Health. There are just over 150 of these bodies each covering a defined geographical area with a population averaging 350,000. They do directly provide some important community services but their main function is commissioning patient oriented health services from secondary providers (hospitals, etc.) and GP practices. They control some 80% of the English NHS budget. In defining outcomes for these organizations, the approach adopted by English central government (not UK because the devolved administrations have different approaches) is the specification of a very detailed set of targets defined in terms of sets of indicators. Under the current regime – a reasonable complaint by health service managers and other personnel is that the UK health service has been subject to continuous managerial revolution – there has been a change from the summary ordinal indicator of performance of the kind previously represented by the 'star' system where four stars indicated high performance and zero poor performance. Instead across a range of domains the PCT is identified in terms of 'Green, Amber and Red' lights. Three Green represents satisfactory performance.

Most PCTs are co-terminous with unitary local authority areas which means that the Local Strategic Partnerships (LSPs) – the 'joined up governance' bodies which bring together PCTs, Local Authorities and a range of other governance bodies at the local level, operate in a straightforward fashion. However, some PCTs cover multiple authority areas. In any event it is the local authority areas – the territorial reach of the LSPs – which are the focus of this study. These Spearhead areas comprise just about half the total set of PCTs and are those where health outcomes have been significantly worse than for the average in England as a whole. Of course the PCTs operate in contexts, that is to say they have environments with health relative impacts. Health outcomes are 'unequal' for the population of their territories, but it is evident that there is a close relationship between health inequalities and general social inequalities and the Spearhead PCTs have territories which contain substantial populations of poor and deprived people. They are also typically located in areas of post-industrial decline. So setting targets which require the PCTs to reduce the gap between cancer and coronary vascular premature death rates, and the rate of teenage conceptions, in their areas as compared with national averages means that they are required to redress through health service activity, inequalities which to a substantial degree originate outwith the form and content of health service provision itself. The formula on which PCTs are funded in relation to their operations includes a

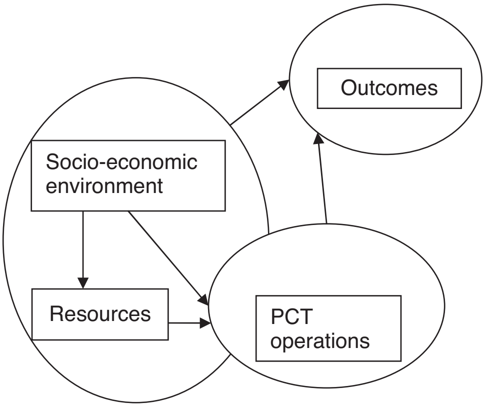

Figure 7.1 The inter-relationships of health outcomes

needs based element, so there is a system based attempt to compensate for general social inequalities. However, most deprived PCTs are not funded fully in relation to this aspect and therefore are in deficit in relation to needs.

It is helpful to construct a process description model of the determination of health outcomes here – noting immediately that of course the set of three 'closing gap' targets set for PCTs are precisely the kind of continuous indicators which I have argued above (following Ragin and Rihoux) are not appropriate in public and social policy. Indeed I am going to work with cluster derived categories as outcomes using not the raw scores but whether gaps are narrowing or not as input into the clustering process. Anyhow, see Figure 7.1.

This figure indicates that the PCT operations are embedded in a local socio-economic environment which has an impact on them and directly on health outcomes. PCT operations have an impact which is in part determined by socio-economic environment but is also a function of their own activities. Resources both reflect environment and contribute to operations. We can visualize this alternatively in Figure 7.2.

Some interesting measurement issues arise. We can describe social context in terms of aggregate data since this plainly is descriptive of the whole social environment. Whilst personal aspects (traditionally in public health we would think of these as personal behaviours), have an influence, we can consider these as themselves products in part of socio-economic circumstances and in any event averaging out to some degree over populations. Our choice of socio-economic indicators is largely conventional. Here we will use some educational indicators and the index of multiple deprivation. Measurement in relation to outputs is also conventional or perhaps determined, in that we can use the 'narrowing'/'widening' measures in relation to the specified targets.

The difficulties arise in relation to measuring thruputs in terms of PCT organization and operations. Gradings determined by external assessors offer one route, and

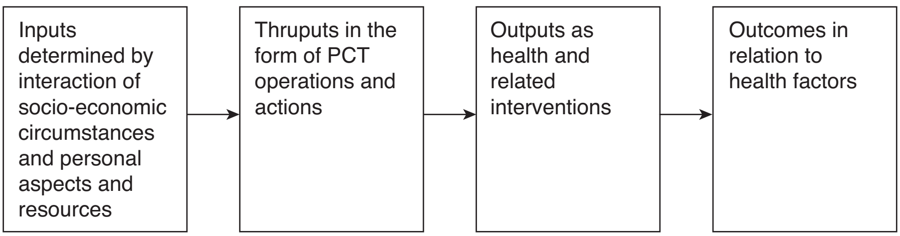

Figure 7.2 The causal chain for health outcomes

Blackman and Wistow have developed a set of self reporting measures interactively with health service managers. In the following both will be employed as in summary as part of an attribute set using Qualitative Comparative Analysis *to explore* complex and multiple patterns of causation in relation to specific outcomes. The method used is binary QCA in which attributes are either present or absent. The focus will be on the truth tables. These consist of lines representing configurations, i.e. combinations of attributes, organized in relation to the presence or absence of a binary outcome. If all the cases which possess a particular set of attributes, i.e. belong in a particular configuration, have the outcome then there is a consistency measure of 1. If none of the cases in the configuration have that outcome there is a consistency measure of zero. A problem even with binary QCA is that with large numbers of variables the number of possible configurations becomes very large – for N variables there are 2^N possible configurations. A method which seems appropriate for this 'set theoretic' approach to causality is to reduce the number of variables by clustering related variables and establishing binary clusters to describe sets. So in this example we are working with the following variables, some of which are based on clustering of sets of related variables:

- Allgreen – the PCT has green scores on all three domains of performance.
- Bincomp – binarized total competency score – less than 18 is low, 18 or more is not low.
- Newdepcl – binary clustering based on social deprivation variable set.
- Newperfcl – binary clustering based on a set of PCT performance measures.
- Cvdactcl – binary clustering based on self assessment in relation to coronary vascular disease commissioning and interventions.
- Cancactcl – binary clustering based on self assessment in relation to cancer commissioning and interventions.
- Narrcan – gap between this PCT and national average for premature deaths from cancer is narrowing.
- Dichotbudg – budget is either below needs target or equal to/above needs target.
- Narrcvd – gap between this PCT and national average for premature deaths from coronary vascular disease is narrowing.

In all the clustering instances, SPSS two step cluster was used and the binary clustering structure emerged as the optimum (see Table 7.1).

Let us examine the second row in Table 7.1. There are three cases and one does not have a narrowing cancer gap. The cases are not all green on performance indicators, are below 18 on overall competency score, are not in the most deprived category in relation to social context, are not high in

Table 7.1 Configurations in relation to cancer outcomes

allgreen	*bincomp*	*newdepcl*	*newperfcl*	*cancactcl*	*dichotbudg*	*number*	*% cases with narrowing cancer gap*
0	0	0	0	0	1	4	25
0	0	0	0	1	1	3	67
0	0	1	0	0	1	2	50
1	1	1	1	0	1	2	50
1	1	1	1	1	1	2	50
0	0	0	0	0	0	1	0
0	0	1	0	1	1	1	0
0	1	0	0	0	1	1	0
0	1	1	0	1	1	1	0
1	1	0	1	1	1	1	0

the performance set, do rate themselves highly in relation to cancer commissioning and intervention, and are below their needs budget level. Configurations lead us immediately to path dependency. Essentially each configuration can be thought of as a cell in a multi-dimensional contingency table, in other words as a polythetic classification set. All the cases in that configuration are the same for values of attributes in the specified attribute set. Of course we do not have a deterministic resolution of outcome for this set but we can now proceed to process tracing by examining the deviant case in relation to the other two cases and exploring what is different between it and them. Note that in contrast with regression based methods this approach makes no attempt to assign a degree of importance to each of the individual attributes. Rather it takes all of them in combination. This is in some ways equivalent to fitting a regression equation, say in a logistic regression, with all interaction terms specified. However, QCA allows for all existing – i.e. actually present among the cases examined – configurations to be addressed at one go which is rather different from a fully saturated regression model. We should also note that there is no significance testing here. It is not at all necessary because, as so often when we work with institutions, we have all possible cases in the data set so no statistical inference is required.

In Table 7.2 we present the configurations for these PCTs in relation to Cardio-Vascular outcomes. It is interesting that all of the pathfinder PCTs fell into the category of assessing current performance across CVD commissioning and interventions as good. It is also interesting that on an individual attribute level there is no systematic relationship between external assessment gradings and outcomes for either outcome set.

The two configuration sets presented are not particularly impressive in explanatory terms but that is not the point here. Rather they offer possibilities for further path dependent exploration. QCA is being used as a screening tool for comparative investigation. They sort things into kinds in relation to causal outcomes and show up similarities and differences in relation to those outcomes.

A crucial issue in relation to the deployment of QCA in causal analyses has been the problem of time. Caren and Panofsky (2005) have developed a method for ordering attributes which takes account of the way in which causal effects may be dependent on the sequence in which things have happened. In the project which generated the data from which Tables 7.1 and 7.2 are taken, the data elicitation included descriptions by respondents of the character of their organization around particular targets three years previously. It is in principle possible to use such 'time before now' description in relation to Caren and Panofsky's approach. However,

Table 7.2 Configurations in relation to cardio-vascular outcomes

allgreen	*bincomp*	*newdepcl*	*newperfcl*	*cvdactcl*	*dichotbudg*	*number*	*% with narrowing CVD gap*
0	0	0	0	1	1	5	80
0	0	1	0	1	0	3	33
1	1	1	1	1	1	3	0
0	0	0	0	1	0	2	50
0	0	1	0	1	1	2	50
0	1	0	0	1	1	1	100
0	1	1	0	1	1	1	0
1	1	0	1	1	1	1	100

there was a real practical difficulty here which has the potential for arising in relation to any organizational study. Respondents were required to construct a reflexive evaluation of the current character and orientation of their organization and also, if possible, to remember back three years and do the same for that time point. Let alone problems of memory, in many instances the key personnel had moved on and the respondents were not able to reconstruct from personal experience any version of times past. Nonetheless a central issue for work of this kind is the elicitation of systematic accounts of previous state as a basis for the exploration of the temporal ordering of complex causation and that requires the construction of histories as part of our exercise. Of course that is exactly what process tracing is – the making of histories focused on the processes of causation.

QCA is an interesting technique with considerable potential and can be used in much more sophisticated ways than represented by the very simple demonstrations presented here. It is possible to work with fuzzy set memberships and with multi value rather than binary attributes. Moreover, the techniques have a 'reduction process' which uses Boolean logic and De Morgan's law to achieve more parsimonious causal descriptions. Ragin (2000) and Ragin and Rihoux (2009) can be consulted for a full description. However, what we want to emphasize here is the qualitative element in the process. Attribute assignation and truth table construction are ways of exploring by summarizing. If we are going to deal with real cases we need to know lots about them. Blackman and Wistow's approach to getting to know lots about them has involved a very detailed quantitative engagement with key informants with the very form of the data construction (note construction, not collection) instrument itself being the product of dialogue with experts who were drawn from the field of informants. At the same time they were able to add to the products of that engagement by drawing on available secondary data describing the cases. The combination of these processes tells us a lot.

However, there is a missing element – a statement made not to criticize, far from it, but rather to demonstrate the forward potential of qualitative work developed from an interpretation of essentially quantitative information. Byrne (2009) has called this process 'machining hermeneutics'. We can find out both what we know about causality and, even more importantly, what we don't know. That takes us forward to more qualitative engagement. In the project examined here we can clearly see that this work can be taken forward by a combination of documentary research and oral testimony to develop a fuller historical account, and ongoing interviews and discussions (including focus groups) with the informant group. In this process we are inevitably engaged in dialogical research. We are not just eliciting information from informants. We are processing it and then taking the results of that processing back to informants for further discussion – we know this much and, even more importantly, don't know this much. Where do we go now? That seems a good note on which to end.

NOTES

1 In academic contexts these include the previous collegiate system of my own university, a much more managed system in a then Polytechnic (and my own university in common with all old UK universities is in transition towards such a system), but perhaps more importantly work in a small community development team and with a range of community organizations and political groups over many years.

2 See *Byrne (2009)* for a development of the implications of this position for our understanding of social measurement.

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8

Complexity, Poststructuralism and Organization

Paul Cilliers

INTRODUCTION

Poststructural perspectives have had a profound effect on the intellectual landscape at the start of the twenty-first century. It has been received with attitudes ranging from blind worship to outright hostility – the one extreme most probably caused by the other. Whether one likes it or not, Poststructuralism has important implications for the way in which we understand the world, and therefore it has to be taken seriously. The resistance to poststructural thought is partly the result of its critique of positivistic and reductionist methods in the natural and social sciences. This critique is often deemed to be anti-scientific or relativistic. A thorough engagement with the tradition of poststructural thinking will show that this is not the case (see Cilliers, 2005a). A critical position does not necessarily imply dismissal, it argues primarily for transformation.

It is particularly fruitful to view Poststructuralism as a position inherently sensitive to the complexity of the phenomena it investigates. This view allows for a two-way interaction: Complexity allows us to generate a more rigorous interpretation of Poststructuralism and Poststructuralism enables us to generate a critique of Complexity which could prevent it from reverting to traditional reductionist perspectives – a real danger.

The impact of Poststructuralism on Management in general, falls outside the scope of this book. The focus here is specifically on how *Complexity* supplements the argument. However, if the discussion is strictly confined to positions which explicitly combine all three notions – Complexity, Poststructuralism and Management – there will not be that much to discuss. This combination needs to be developed further, and we will return to this development towards the end. The strategy will therefore be to unpack the varied relationships between Complexity and Poststructuralism in a way that will open up the possibility for future work in organizational studies. To make this possible, some reflection is required on how the notions 'complexity' and 'poststructuralism' will be used in this chapter.

COMPLEXITY

Since Complexity is the theme of the book, the basic ideas will not be explained here.

It is necessary however, to make two important points which reflect some of the differences and tensions in how the notion is understood.

In the first place, one should maintain a distinction between Complexity and Chaos. These notions share a certain history, but are sometimes intertwined with too much ease (e.g. Taylor, 2003). It may be useful to reserve the notion 'chaos' for that slice of theory concerning itself with deterministic and recursive nonlinear equations, fractal mathematics, self-similarity, bifurcations, power laws and universal constants. 'Complexity' refers to a more general understanding of complex systems which focuses on (nonlinear) relationships, systemic interaction, boundary problems, emergence and adaptation. Maintaining this distinction is significant since it results in a completely different understanding of the limits of what we can do with Complexity, which brings us to a second distinction.

By its very nature, Complexity is a diversified field (Heylighen et al., 2007). The differences between some strands are of such a nature that they lead to different if not opposing epistemologies. Edgar Morin (2007) explicates these differences by distinguishing between what he calls 'restricted' and 'general' complexity.[1] Restricted complexity is, for Morin, exemplified in those approaches to complexity that developed from chaos theory and fractal mathematics. These approaches focus on underlying patterns and universal principles which are still highly reductive in nature.

> Restricted complexity made […] possible important advances in formalization, in the possibilities of modelling, which themselves favor interdisciplinary potentialities. But one still remains within the epistemology of classical science. When one searches for the 'laws of complexity', one still attaches complexity as a kind of wagon behind the truth locomotive, that which produces laws. A hybrid was formed between the principles of traditional science and the advances towards its hereafter. Actually, one avoids the fundamental problem of complexity which is epistemological, cognitive, paradigmatic. To some extent, one recognizes complexity, but by decomplexifying it. In this way, the breach is opened, then one tries to clog it: the paradigm of classical science remains, only fissured. (p. 10)

General complexity, Morin argues, is not merely a methodology; it involves a rethink of our fundamental definitions of what knowledge is. When dealing with complexity, the traditional method of analysis does not work. What is more, the divide between subject and object cannot be maintained in any clear way. This is how Morin formulates it:

> In opposition to reduction, [general] complexity requires that one tries to comprehend the relations between the whole and the parts. The knowledge of the parts is not enough, the knowledge of the whole as a whole is not enough … Thus, the principle of reduction is substituted by a principle that conceives the relation of whole-part mutual implication. The principle of disjunction, of separation (between objects, between disciplines, between notions, between subject and object of knowledge), should be substituted by a principle that maintains the distinction, but that tries to establish the relation. (pp. 10–11)

From this formulation it should be clear that Morin is not advocating a relativistic position, nor is he arguing for a 'generality' which is naively holistic or vague. One cannot say anything without making distinctions, but these distinctions are always contextualized within a set of relationships (Morin, 2007: 18–20). If one is concerned with the understanding and modelling of specific phenomena which are bounded more or less clearly, then one naturally operates within the ambit of restricted complexity – as long as one remembers the associated limitations (Georgiou, 2000; Cilliers, 2005b). If one is concerned with complex (social) phenomena which are volatile, self-reflexive, adaptive and where boundaries are ill-defined, restricted complexity is less useful.

The problem, one Morin agrees with, is that there is no unambiguous discourse for dealing with general complexity. It operates on a level which includes interpretation and disruption.

The object of discussion and the discussion itself are folded into each other. There are normative issues which cannot be eliminated. We are in trouble.

It is exactly in the recognition of this 'difficult' position that Poststructuralism provides an intellectual strategy which helps us in or engagement with a complex world. It provides us with reasons why restricted, reductive strategies fail, and it opens up a space where innovation can take place. This combination of complexity thinking and poststructural critique leads to something I would like to call Critical Complexity.

POSTSTRUCTURALISM

Although much more specific than the label 'postmodern', the term 'poststructural' is nevertheless used to refer to a group of positions which contains sharp differences. It would be extremely reductive to lump Derrida, Foucault, Lacan, Levinas, Lyotard, Deleuze, Guattari and Althusser together under a single description. The scope of this chapter unfortunately does not allow us to explore all these differences.[2] As always, when dealing with complex things (Cilliers, 2002), some generalization and reduction is required.

In the present context, the notion 'structuralism' refers to the set of ideas which developed out of the work of the linguist Ferdinand De Saussure and the anthropologist Claude Lévi-Strauss. For both of them the meaning and significance of linguistic and social things result from the relationships between them. In order to understand such things one should not look for some 'essential' meaning, rather one should unpack the structure of the sets of relationships which constitute these objects. Thus both were essentially 'system' thinkers.[3] Nevertheless, similar to approaches in restricted complexity, they believed that if you worked hard enough, you could uncover the structure of the system, and thus get it 'right'.

Poststructuralism builds on the essential systemic 'method' of structuralism by supplementing, or deconstructing it with insights from amongst others Nietzsche, Freud, Marx, Heidegger and Bataille. Perhaps the most important philosophical result of this development of structuralism is the claim that the meaning of things can never be closed down or finalized.[4] The very structures which make meaning possible introduce a distortion in the system of relationships. These structures, sometimes called hierarchies, can therefore not be final, but are in constant transformation, both through external intervention and by their own dynamics. This process is what is often called 'deconstruction' – a term which has nothing to do with destruction. As a result, the poststructural position has a number of important implications, also for how we think of organizations and management. It suggests that:

1 A system is constituted relationally. These relations, following Saussure, are relations of difference. The differences in a system are therefore crucial. Attempts to reduce the difference will destroy its complexity. This realization is central to the work of especially Derrida and Deleuze.
2 If a system is constituted through a vast array of nonlinear relationships in constant transformation, and the meaning (emergent properties) of the system is a result of the play of these relationships and not of some essential characteristics of the components of the system, then we cannot have complete knowledge of complex systems. The introduction of some metaphysical position in order to fix the play of differences, and thereby the meaning, cannot capture this dynamic complexity.
3 There is no objective or neutral position from where we can give a complete description of complex systems like language, society or organizations. We have to 'frame' these descriptions. There can be no meta-position which can be used to determine the correct frame – the complexity would then have to be known at that level. Consequently, there are always normative issues involved in the way in which we approach systems. To claim objectivity is thus, from the poststructural perspective, not only technically incorrect, it is unethical.

These insights can be examined in a little more detail with specific reference to the different understandings of Complexity discussed above.

POSTSTRUCTURALISM AND COMPLEXITY

In this section the way in which Complexity and Poststructuralism inform each other will be explored in a general way, primarily following Morin's characterization. In subsequent sections the focus will be on more specific thinkers. Morin himself is not a poststructural thinker, nor is his position directly informed by it. Nevertheless, he is a sophisticated thinker of complexity (see Morin, 2008). His arguments help to clarify the relationship we are concerned with, without introducing too much philosophical jargon.

The first important insight follows from his description of a 'restricted' understanding of complexity. This understanding can clearly be related to the Saussurian position. It acknowledges the basic structure of complexity, but balks before its more radical consequences. In Morin's terms, it opens up the understanding towards relational thinking, but it cannot get rid of the reductive apparatus that should qualify this work as 'science'. As a result, this approach to complexity – and one could put a fair amount of the work done under the umbrella of the so-called Santa Fe School in this category – reverts to an instrumental strategy in the hope of making purely objective claims in the same way as Saussure's claim that we can get at the correct meaning of the sign. It is precisely this denial of a normative element in our dealing with complexity which makes this position 'restricted'. In developing a deeper understanding of what a 'general' understanding of complexity could be, something for which Morin thinks we do not yet have a language, insights from deconstruction could play a vital role.

One such insight could be the idea of the 'double movement'. Derrida argues that the strategy of deconstruction involves a 'double' activity. In deconstructing a system, one has to make use of the resources provided by the system itself. One is thus simultaneously confirming and undermining central elements of the system. This simultaneous give and take is a much more complex process than simply replacing something with something else. It implies that one transforms something by using the thing itself in novel ways. Deconstruction is thus not a critique from the outside, a critique which knows where it stands and what it wants to do. It is a critique which acknowledges that it is in transformation itself because it cannot depart from a perfect understanding, neither of itself, nor of that which it is transforming.

In *On Complexity* Morin (2008) describes the way in which he thinks we should deal with complexity in very similar terms to that of deconstruction. He argues that when dealing with complexity, we cannot escape contradiction, and that we should not mask this contradiction with a 'euphoric vision of the world' (p. 42).

> [The order/disorder/organization relationship] is a typically complex idea in the sense that we have to bring together two notions – order and disorder – that logically seem to exclude each other. In addition, we might think that the complexity of this idea is even more fundamental. … We arrive by entirely rational means at ideas that carry a fundamental contradiction (p. 41)

He continues:

> In the classical view, when a contradiction appears in reasoning, it is a sign of error. You have to back up and take a different line of reasoning. However, in a complex view, when one arrives via empirical rational means at contradictions, this points not to an error but rather to the fact that we have reached a deep layer of reality that, precisely because of its depth, cannot be translated into our logic. (p. 45)

The point he wants to emphasize is that we cannot deal with complexity without employing a self-critical rationality, that is, a rationality which makes no claim for objectivity, or for any special status for the grounds from which the claim was made.

> Humanity has two types of madness. One is obviously very visible, it's the madness of absolute incoherence, of onomatopoeia, of words spoken randomly. The other is much less visible: it is the madness of absolute coherence. Against this second madness, the resource is self-critical rationality and recourse to experience. (p. 48)

In order to maintain this self-critical rationality, he argues 'that there are three principles that can help us to think complexity'. The first he calls 'dialogic'. 'The dialogic principle allows us to maintain the duality at the heart of unity. It associates two terms that are at the same time complementary and antagonistic'. (p. 49)

The second principle is that of 'organized recursion'. This principle argues for an understanding which 'has broken away from the linear idea of cause and effect, of product/producer or structure/superstructure, because everything that is product comes back on what produces it in a cycle that is itself self-constitutive, self-organizing, and self-producing'. (pp. 49–50)

The third is the 'holographic principle'. This principle argues that the characteristics of a system is distributed, not localized. The activities of the parts *and* the occurrences on the macro-level participate in producing the system. 'The idea of the hologram surpasses both reductionism, which can see only the parts, and holism, which sees only the whole' (p. 50)

These three principles are clearly interlinked. The holographic principle is an effect of the recursive principle which is linked to the dialogic principle. This constellation of ideas thus argues for a kind of double movement, an acknowledgement of the play of *différance*, very similar to that of deconstruction. There is a coupling between the *what* is being observed and *how* it is being observed; they are folded into each other. Despite our bravest attempts, we cannot extract ourselves from these folds cleanly. Nevertheless, this is what we do, and, in a contradictory way, *have* to do when we do science.

> … every system of thought is open and contains a breach, a gap in the opening itself. But we have the possibility to hold meta-points of view. The meta-point of view is only possible if the observer–conceiver integrates himself or herself into the observation and the conception. This is why complex thought requires the integration of the observer and the conceiver in its observation and conception. (p. 51)

The kind of understanding of complexity proposed here certainly does not produce a clear 'method' which can be followed in any automatic way.[5] Morin is also clear on this: 'I can't pretend to pull a paradigm of complexity out of my pocket' (p. 51). When we deal with complexity a certain 'modesty' is inevitable (Cilliers, 2005a). That does not imply that we are disempowered. It means that we have to engage with these complexities in a creative way. Two paradigms of this engagement can be mentioned specifically: approaches which involve the work of Derrida and of Deleuze.

COMPLEXITY AND DERRIDA

Derrida (1988: 119) famously claimed that 'if things were simple, word would have gotten around'. Despite the fact that he did not engage with Complexity in any direct way, his whole oeuvre displays an acknowledgement of the complexity of the world we live in. His reflections on language and the emergence of meaning in particular can be used to make links with Complexity specific.

Saussure (1964) describes language as a system of signs where the signs acquire their meaning through their relationships (of difference) with other signs. The collection of differences which constitute each sign add up to its meaning, what Saussure calls the 'signified'. This meaning, for him, is structurally determined in this way. Derrida deconstructs this position by showing that the play of differences – or *traces*, as he calls them – is perpetual. Every constituted meaning immediately re-enters into the network of interaction, thereby transforming it. In this way, the meaning is never determined, but always postponed. He coined the term *différance* to describe this process. Meaning is not only the result of difference, but also of deferral. In this way he introduces a temporal dimension to the way in which meaning emerges.[6]

A complex system can be seen as a network of dynamic nonlinear relationships (Cilliers, 1998: 2–7). These relationships can be equated with Derrida's notion of traces. The dynamics of the system is a result of all the interactions in the system, but since this interaction also consists of multiple simultaneous nonlinear feedback, with a constant flow of energy through it, it operates in a state far from equilibrium. This perpetual activity is in effect a form of *différance.* This notion is extremely useful to describe the way in which the emergent properties of the system can manifest themselves, yet be in constant transformation. Always already but never quite.[7]

The way in which something can have manifest meaning, yet simultaneously be in transformation, is best described by Derrida's notion of *iterability.*[8] For him, a sign has to be recognizable *as that sign*, but this fact does not determine the meaning of the sign. Since the sign, when used again, operates in a different context, different relations come into play which will animate the meaning of the sign differently. *Iterability* is a notion which ties repeatability with alterity (Derrida, 1988).

If these ties between Deconstruction and Complexity hold, it also has implications for our knowledge of complex systems. Since the system is in constant transformation – as a result of large numbers of nonlinear interactions with feedback – the emergent properties can never be simply reduced to some specific state of the system. In fact, they are in constant transformation themselves. It is thus not possible to know them in any final way. Our understanding is thus always partial and provisional. This does *not* mean that our knowledge is arbitrary, but it does mean that the knowledge produced through (inevitable) reductive means should not be presented as final or complete (Cilliers, 2000, 2005a).

Reflections on complexity form a central part of the work of Niklas Luhmann. He is not a poststructural thinker, thus a discussion of his ideas falls outside the scope of this chapter. Nevertheless, a number of thinkers (Baecker, 2001; Teubner, 2001; Bjerge, 2006) use the work of Derrida to supplement Luhmann's ideas. Teubner emphasizes the differences between the two, arguing that Luhmann tries to resolve the paradoxes of complexity which Derrida insists should be kept alive. For Teubner, and Bjerge, it is exactly the working of *différance* that interrupts the closure produced by autopoiesis and thereby resists Luhmann's move towards deparadoxification. Baecker focuses more on the problems of causality, but insists that Luhmann's understanding of systems already contains a deconstructive element, although this can be expanded through the working of *différance.*[9]

There is of course also resistance to the idea that poststructural thinking resonates with complexity. Morcol (2002) finds Poststructuralism too relativistic, and argues that we should rather look to the postpositivist ideas of Popper, Kuhn and Feyerabend if we wish to remain in the realm of what can be called 'scientific'.[10]

COMPLEXITY AND DELEUZE

Like Derrida, Deleuze is a wide-ranging and disruptive thinker. Although they differ from each other in many respects, they share a number of central concerns, in particular a concern with the centrality of 'difference' and with moving beyond conventional ethics. Protevi (2001: 1) argues that Complexity theory provides a framework within which these two thinkers can be placed in dialogue.[11]

Deleuze also disrupts this chapter somewhat. There is no doubt about his appropriation of concepts from Complexity. Nevertheless, when he and his regular co-author Guattari refer to Complexity, it is mostly to ideas from chaos, fractals and the non-equilibrium dynamics of Prigogine (see Escobar, 2000; Popolo, 2003; Bonta and Protevi, 2004). This may lead one to suspect that Deleuze could fall in the category of 'restricted complexity', and some critics indeed argue something of this kind (see Badiou, 1999; Žižek, 2003). All the same, there is no doubt about the fruitfulness of Deleuze's employment of these terms, and there is really no way in which he can be classified as a reductive thinker.[12]

Deleuze's central philosophical concern is with the notion of 'difference'. One of his foundational texts remains *Difference and Repetition* (Deleuze, 1994) and Ansell Pearson (1997) refers to him as 'the difference engineer'. 'Difference' Deleuze argues, should not be seen as the difference between things which already have an identity. To the contrary, identity is the result of the combination of differentiations. Just as in a complex system, identity is constituted through relations of difference. Thinking Complexity means thinking difference. Repetition is never the recycling of the same. Difference simultaneously has a unifying and a creative component.

The Deleuzian notion which resonates most strongly with Complexity, is that of the 'rhizome'.[13] This notion describes the non-hierarchical, systemic relationships between things. Similar to Derrida's notion of 'trace', the rhizome does not signify by itself, it relates, and can be described by six principles, summarized by Bonta and Protevi (2004: 136) as follows:

> connection (all points are immediately connectable); heterogeneity (rhizomes mingle signs and bodies); multiplicity (the rhizome is 'flat' or immanent); 'asignifying rupture' (the line of flight is a primary component, which enables heterogeneity-preserving emergence or 'consistency'); cartography (maps of emergence are necessary to follow a rhizome); decalcomania (the rhizome is not a model like the tree, but an immanent process).

The affinities with a network model of complexity are clear.

Given the importance of a foundational difference and of rhizomatic interaction, it follows naturally that the notion of 'emergence' can also be investigated in a Deleuzian context. Following DeLanda (1997, 2002), Protevi (2006) does this by elaborating the differences between emergence as an autopoietic activity as described by Maturana and Varella, and the dynamic emergence resulting from a rhizomatic process. Autopoiesis, argues Protevi, remains caught in a model of homeostasis, whereas emergence for Deleuze and Guattari is in itself a dynamic process with a logic tied to perpetual change.

Two of the central thinkers who develop and apply the work of Deleuze with reference to Complexity are Ansell Pearson (1997, 1999) and DeLanda (1997, 2002). In *Germinal Life*, Ansell Pearson (1999) situates Deleuze within a tradition of biophilosophy in the company of Darwin, Bergson and Freud. These authors, while elaborating very different positions, were all sensitive to the philosophical consequences of insights gained from natural science. He points in particular, to the appropriation of Bergson and contemporary complexity theory as a turn to self-organization in Deleuze and Guattari's thought. Ideas from Complexity allow Deleuze and Guattari the conceptual tools to think about living systems as dynamical systems which are not passive in their adaptation to the environment. Unlike Freud, they do not understand evolution as an accident determined by the outside acting on a passive organism (p. 40); and unlike Darwin, they also do not think at the level of the species. Change and transformation are intrinsic to form.

DeLanda's central thesis in *A Thousand Years of Non-linear History* is that everything around us – mountains, animals, people, cities, languages – are structures that have arisen from complex and contingent historical processes. Through this analysis, he claims that the same structures of difference and individuation created history, language and rocks (p. 215). He suggests that complexity thinking in the physical and natural sciences has been sharpened over the past few decades, but that the same has not happened in the human sciences (p. 14). The methodologies of the physical sciences are of philosophical significance and thus there is a need to engage with them. One way would be to theorise the 'nonlinear dynamics of human interaction' (p. 15).

DeLanda (2002) continues the argument in *Intensive Science and Virtual Philosophy* where he focuses again on Deleuze's ontology. Deleuze's materialism is given a special place apart from other postmodern philosophical positions. De Landa weaves complexity thinkers such as Kauffman and Prigogine into the corpus of his argument. These scientific arguments, he claims, take Deleuze's philosophy from the metaphorical to the material.

Despite its often esoteric nature, the work of Deleuze is seen to have practical implications. It is sometimes referred to as 'geophilosophy' (e.g. Bonta and Protevi, 2004) and both Ansell Pearson and DeLanda find the implications for biology important. We will briefly look at some implications for organizations below.

COMPLEXITY AND POSTMODERNISM

The notion 'postmodern' has come to mean so many different things, that it cannot be given a coherent overview. The term is nevertheless often – and often incorrectly – used to refer to poststructural thought. There are a number of relevant papers which make general reference to a varied number of postmodern thinkers in the context of Complexity. These include Clark (2000, 2005), Dillon (2000), Urry (2002), Lafontaine (2007), Morais (2008), and Dillon and Lobo-Guerrero (2009). For a very insightful discussion in the context of Management, see McKelvey (2002, 2004).

It is also clear from an overview of the literature that thinkers like Deleuze and Derrida have been associated with complexity more often than thinkers like Foucault and Lacan. Hayles (2000) does explore some implications of their positions. Dillon and Lobo-Guerrero (2009) revisit Foucault's biopolitics in light of developments in complexity theory as it has emerged in the study of life and organization.[14] Cowling (2006) criticizes a Lacanian position (via chaos theory) in the context of criminology.

Postmodern attitudes often elicit severe criticism, of which a good example is the so-called 'Science wars' triggered by Alan Sokal (Sokal and Brickmont, 1998). There is not space here for a defence against these often ill-informed accusations (see Cilliers, 2005b), but it is worth noting that there is space opening up in which a new interaction between different traditions can take place. Byrne (1998), for example, is critical of both dogmatic reductionist arguments and of relativistic postmodern positions. He prefers to explicate his position in the context of critical realism. Nevertheless, he also recognizes the reductive tendencies in some complexity theorists and argues for a more nuanced, pluralist position employing case based comparisons.

ISSUES IN ORGANIZATION

As indicated in the Introduction to this chapter, the literature that explicitly combines Complexity, Poststructuralism and Management is limited. This is especially the case if one maintains a distinction between Chaos and Complexity. Linstead (2004) edited a useful volume on links between Organization Theory and a number of postmodern thinkers, but there is little reference to Complexity.[15] One has the feeling that there are a number of important ideas contained in the relationship between Complexity and Poststructuralism which still need to be worked out in the context of Management and Organizational Theory. A few of them can be framed briefly.

Poststructural philosophy is often concerned with the notion of the boundary – what is 'in' and what is 'out'. Studies of complex systems share this concern. Complex systems are open; their environment is co-constitutive of the system. It is often difficult, if not impossible, to determine the boundary of many systems. Identifying the boundary can be as much an effect of your *description* of the system as of the system itself. The choice of boundary will determine one understanding of the system. Since the choice of boundary is usually not a 'neutral' act, our understanding of the system is not 'neutral' either. This has clear implications for how we understand an organization. What belongs to the organization and what does not? What is the relationship between the organization and its environment, and what *is* its environment? How flexible should boundaries be? Organizations clearly have boundaries, but how we conceive of them will affect the way we understand it, and the way in which we intervene and interact with it (see Georgiou, 2000; Cilliers, 2001; Clark, 2005).

Complex systems, like organizations, are not chaotic. They have structure and are often robust. The 'nature' of this structure should be examined in detail. For example, if there is structure, there are hierarchies, despite the fact that the system is not determined by these hierarchies alone, and that the hierarchies are not neatly nested (Cilliers, 2001). The existence of hierarchies, and the way in which they are subverted and transformed is one of the central issues in deconstruction (see e.g. Culler, 1983: 85–110).

If the structure of systems, like organizations, are in constant transformation, one should be concerned with the rate of this transformation (Cilliers, 2006). Not enough work has been done on the temporal nature of complex systems. Derrida's notion of *différance* can be extremely useful in this regard since it ties the temporal to the spatial.[16]

The issue of difference and identity was discussed in the context of Poststructuralism above. This issue is also vital for our understanding of an organization. How do we understand and develop the identity of an organization? What is part of that identity? Do we need a specific identity at all, or is the identity in itself a divided thing? How do we deal with differences within the organization? How do these considerations impact on notions like a 'mission statement' or the idea of 'core business'? Any organization will have an identity – even if it is not the one it thinks it has, or the one it wants – but this is not something simply decided on by management or something fixed by a statement of intent. Identity is historically constituted and is constantly deconstructed (see Cilliers and de Villiers, 2000; Cilliers and Preiser 2010).

Perhaps the most important result of the interaction between Complexity and Poststructuralism is the significance it finds in ethical and political considerations. This issue has been explored (Kellert, 1996; Protevi, 2001; Clark, 2005; Dillon and Lobo-Guerrero, 2009; Fenwick, 2009), but there is much urgent work to be done in this respect.

The poststructural perspective urges a certain inversion. Ethics is not something we 'also do', it constitutes our knowledge of complex things, and this 'knowledge' constitutes who we are – where 'we' can refer to both individuals and organizations. The argument can be made from Complexity in the following way: We cannot know complex things in their complexity. We have to reduce the complexity in order to grasp anything. Since there is no meta-position from where this reduction can be done objectively – the 'framing' problem – we have to make certain choices. These choices introduce a normative component into our very understanding of complexity. What we leave out may seem trivial, but since the remainder (the 'supplement' in deconstructive terms) has a nonlinear relationship with the rest of the system, we cannot predict the magnitude of the error produced by the reduction in time. When we consider the boundary of the system under investigation, we are not simply engaged in a technical task, we are *ethically* involved (see Cilliers, 2004, 2005b).

A number of ethical considerations do form part of 'conventional' reflection on organizations. These include notions of responsibility, accountability, respect and trust. Acknowledging complexity affects these considerations in a twofold way. In the first place, these considerations are not peripheral to the essential nature of the organization. They are part of what constitutes the organization. In the second place, many issues which may appear not to be specifically ethical, like hierarchical structure, business plans, mission statements, financial statements, infrastructure, as a matter of fact, everything, has ethical import.

When we talk of the 'ethical organization', we are not simply talking about something which should run more efficiently – although that is not excluded in any way. We are talking about projecting into a better future for all of us.

CONCLUSION: AN ETHICS OF PROVISIONALITY

The links between Complexity and Poststructuralism do not lead to a 'positive' programme which spells out precise strategies with exact goals. What emerges is a more 'modest' attitude which is critical at heart. It is concerned with limits and with reflection. It is not destructive, but transformative. It acknowledges the historical nature of what we are, but it does not see us as being determined by that history. It is sensitive to the enormous ethical and political problems we face, and it urges that we engage with them. Since we cannot have complete knowledge of complex things we cannot 'calculate' their behaviour in any deterministic way. We have to interpret and evaluate. Our decisions always involve an element of choice which cannot be justified objectively. What is more, no matter how careful our actions are considered, they may turn out to have been a mistake. Thus, acknowledging that values and choice are involved does not provide any guarantee that good will come of what we do. Complexity tells us that ethics will be involved, but does not tell us what that ethics actually entails. The ethics of complexity is thus radically or perpetually ethical. There is no *a priori* principle we can follow nor utility we can compute. We do not escape the realm of choice.

The perspective from Complexity via Poststructuralism thus constitutes a radically critical position. The question is, can it be made more substantial? A first response would be that it is better to make the value judgements explicit than to claim a false objectivity. In this way the complexity of the problem can be opened up and the differences respected. But perhaps the critical position itself constitutes a kind of ethical strategy. An initial attempt can be made by acknowledging the following aspects of the critical view argued for:

1 our knowledge of complex things is radically contingent in both time and space;
2 since we cannot predict its outcome, any decision we make concerning something complex has to be irreducibly provisional; yet
3 we have to act in a way which distinguishes the action from its alternatives otherwise we are not acting at all;[17]
4 meaning emerges through the mutual interaction (both constraining and enabling) amongst components in the system, not through some pre-defined essence. Thus, as subjects we are constituted through interactions with others (both human and non-human) around us. My state depends on the state of others.[18]

These principles can, following a sort of Kantian logic, be reformulated in the form of an imperative, what one could call the Provisional Imperative. The following are possible ways of doing it:

1 justify your actions only in ways which do not preclude the possibility of revising that justification;
2 make only those choices which keep the possibility of choice open;
3 your actions should show a fundamental respect for difference, even as those actions reduce it;
4 act only in ways which will allow the constraining and enabling interactions between the components in the system to flourish.

The general importance of a critical position, especially in the context of organizations, is still to be developed in detail, these are just first steps. It is important to show that such a position does not entail negativity or inaction, but that it is nevertheless critical to remain perpetually critical. Three characteristics of such a position can serve as a platform for such a development.

A critical position informed by complexity will have to be *transgressive*. It can never simply re-enforce that which is current. Transformation takes place continually, despite all efforts to contain it. In this respect, I would argue, we need some bold alternatives to the orthodoxy of liberal democracy and a brash capitalism. We should resist the macho nature of most political and economic cultures, irrespective of whether it is politically correct to do so or not. We should not be coerced, frightened or shamed into a state where we relinquish being transgressively critical.

A critical position will, in the most positive sense of the word, be an *ironical* position. There is no final truth which operationalizes our actions in an objective way. Irony also implies, in a very systematic way, a self-critical position. Given the horrors of the world, this claim may be controversial. Nevertheless, we require a sense of humour if we are not to lose our humanity.

In the third place, a central role for the imagination is indispensable when we deal with complex things. Since we cannot calculate what will or should happen, we have to make a creative leap in order to imagine what things could be like. Aesthetic and creative activities are thus not interesting diversions, they open up the possibility of imagining better, more sustainable futures.

Organizations are an inextricable part of the social fabric. The future of humanity depends on their role. We should therefore not only think of organizations in a functional way, but also, or perhaps primarily, in an ethical way. The development of an understanding of organizations and what they do, which takes the provisional ethics of Complexity seriously, stands as a challenge.

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NOTES

1 These may not be the best terms to use, but they have gained a certain currency. Byrne (2005) distinguishes between what he calls 'simple' complexity and 'complex' complexity. He maintains, like Morin, that simple (restricted) complexity plays in the court of current orthodoxy:

> This is why simplistic complexity is so attractive to the worst sort of evolutionary psychology and contemporary ideologues of market models. Write a few rules – the selfish gene, the territorial imperative, profit maximization, rational choice, or, preferably, a combination of all of these, and away we go. Simplistic complexity does deal with a kind of complex emergence but it remains reductionist. (p. 103)

2 For introductions to some of these issues, see Culler (1983), Harland (1987), Ansell Pearson (1997) and Norris (1997).

3 For a further discussion on the importance of recognizing 'systems', especially in the social sciences, see Pickel (2007).

4 Although this may be more true of Derrida than, of say, Foucault.

5 Carol Grbich (2004) attempts to spell out some implications for doing social research. The book is also a useful introduction to the relationships between Complexity, Poststructuralism and the Social Sciences. Complexity and Chaos are more or less equated, and none of the themes is discussed in depth, but the text is accessible and can serve as a first encounter. See also Ketterer (2006) for a view from Chaos.

6 Further aspects of the temporality of complex systems are discussed in Cilliers (2006).

7 For more detail, see Cilliers (1998: 37–47).

8 This is a term of art in deconstruction – not equivalent to the way the notion 'iteration' is used in mathematics or computational theory. A misunderstanding of this notion has lead to some misguided critique of deconstruction, particularly by Searle. See Culler (1983:110–134) and Derrida (1988).

9 An excellent array of discussions on Luhmann, Complexity, Poststructuralism and Ethics can be found in Rasch and Wolfe (2000).

10 See also Eve et al. (1997).

11 See also Clark (2000, 2005).

12 For a defence against the accusation that Deleuze is inaccurate in his use of notions from science and complexity, as argued by for example Sokal and Bricmont (1998), see Marks (2006).

13 Deleuze and Guattari (1987) unpack this notion in *A Thousand Plateaus*, particularly in the introduction.

14 See also Olssen (2008).

15 See also Linstead and Thanem (2007).

16 See Culler (1983: 95–97) and Cilliers (1998: 44–45).

17 These characteristics resonate with what Derrida, in *The Force of Law,* calls the *aporia* of justice. This similarity, and the similarity with Morin's idea of a general complexity, still needs careful elaboration. The idea of the provisional imperative can also be used to explore Derrida's notion of the 'quasi-transcendental'. See Cornell (1992), Derrida (1992) and Morin (2007, 2008).

18 These ideas are elaborated on in Cilliers (2001) and Cilliers and de Villiers (2000).

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9

Causality and Explanation

Alicia Juarrero

INTRODUCTION

Studies on organization and management made their appearance at a moment in history when the natural sciences were not only well established; they were veritably basking in the string of spectacular experimental and theoretical discoveries that marked the first decade of the twentieth century. Although the concept of a division of labor can be traced as far back as Plato's Republic, Henry Ford's revolutionary implementation of the notion arguably provided the impetus to adapt scientific discoveries to principles on workplace management, and thereby transformed productivity and the way business conducts itself. The term scientific management appeared during these extraordinary times.

It was to be expected, therefore, that the cognitive scaffold defining what even counted as scientific – and what didn't – would provide the intellectual foundation around which theories of organization and management would be based. Chief among these often uncritically accepted ideas were the concepts of causality and explanation. That causal forces everywhere operated like colliding billiard balls and could be explained as such; that small perturbations produced only small effects; that what appeared to be a tangled mesh of causal influences could in principle be disentangled into one-to-one relationships in which one cause inexorably led to the one effect – these were a few of the many assumptions embodied in the Newtonian clockwork worldview. They were also the assumptions that informed the principles of scientific management.

Until the seventeenth century, philosophy and science's understanding of causality was governed by rules laid down by Aristotle in works such as the Physics and the Metaphysics. Adequate explanations of anything, Aristotle argued, must make reference to the four causes responsible for any phenomenon. These causes are: final cause (the goal or purpose toward which something aims); material cause (the stuff out of which it is made), and efficient cause (the force that brings the thing into being). The fourth cause, formal cause, refers to the essential properties that make something that kind of thing and no other – the information in its dictionary definition. Aristotle's account of causality, however, includes another claim: that nothing, strictly speaking, can move, cause, or act on itself in the same respect.

Unlike the four Aristotelian causes, most of which was discredited during the scientific revolution wrought by Newton and his contemporaries, this second principle – that anything caused is caused by something other than itself – remained unchallenged until recently. It was also an influential if unrecognized assumption permeating academic discourse, including works on business and management.

A number of different but interrelated assumptions were entangled in the cognitive map drawn by the revolution that ushered in modern science:

1 *Isolated, closed systems.* Real phenomena are enmeshed in their environment. But after Galileo's success in determining that a falling body falls with uniform acceleration despite the apparent interference of friction and other contextual disturbances, the methodological principle that any system, whether natural or manmade, could be studied as if it were a closed isolated system under examination in a laboratory became an inviolable pillar of scientific method. The principle that abstract, universal rules could also be discovered to govern organizations belongs to this tradition.
2 *Analytic reductionism and atomism.* The laboratory science approach was accompanied by Francis Bacon's and Rene Descartes's emphasis on analytic method. Despite Rene Montaigne's warning that one must kill and dissect to analyze, modern belief in reductionism was also buttressed by the works of David Hume and other empiricists who argued that wholes are no more than the sum of their parts. With this principle the scientific revolution of the seventeenth century abandoned the organismic philosophy of Aristotle in favor of the belief that atomic particles are the fundamentally real constituents of the universe. Holism became irrelevant as formal cause dropped out altogether from the scientific picture.
3 *Acontextuality.* All advances in knowledge, accordingly, were believed to originate in careful study of those essential, primary properties of fundamental particles, such as mass, all of which are identical to each other. Any other properties such as those resulting from either the particles' relations with their environment (such as temperature and color), or those due to their combination, were thought not to identify truly emergent characteristics. These features were not a part of the 'furniture' of the world; they were merely subjective and secondary. In a Newtonian world of absolute space and time, context and circumstance become irrelevant and the goal of science is to formulate universal eternal laws that apply everywhere and at any time. The reality of wholes was thus reduced once again to that of aggregates with no novel or real characteristics of their own; as a result, any consideration of formal cause, or of the possibility that the environment or niche in which an organism is situated might be partially responsible for its very nature, was excised once again from scientific discourse.
4 *Randomness and emergence.* As evidence of the interrelated nature of all these assumptions, determinism in turn supported the belief that bringing something entirely new into being is impossible. Underwriting the principles of atomism and determinism, and the view that wholes are inert epiphenomena, was the unquestioned belief that all change was the mere unfolding of potentialities which became manifest as secondary, unessential alterations. Randomness, postulated as the source of novelty since Plato, could not be real, it was believed, because foundationally nothing essentially changed.
5 *Atemporality and irreversibility.* Newton's equations of motion, the paradigm to which all sciences aspired for centuries, are atemporal and as such permit both precise retrodiction as well as prediction. Despite the fact that our intuitive understanding of causal relations are dynamic and temporal, the Newtonian framework assumed an eternal present: Newton's equations are reversible, making it as possible to retrodict as well as to predict.

The mathematics of science adopted in the seventeenth century thus warranted the exclusion of any form of goal-directedness from nature. Along with the elimination of formal cause, this concomitant banishment of final cause from ontology was a principle that once again fit in with the reductionistic method mentioned above, according to which particles in motion are the only constituents of reality. The resulting world view was that of a stable clockwork universe with no remarkable fluctuations; it was, not coincidentally, also a worldview that held out the very attractive promise of absolute control.

CAUSALITY

Once an essentialist, atomistic ontology was in place, Aristotle's four causes reduced to one, the forceful impact of one atom on another, a process, moreover, that obeys laws that can be mathematically formulated in strictly (one to one) deterministic, reversible equations. That these equations described mathematically abstract entities gave no pause to modern scientists and philosophers: as mentioned earlier, since contextual relations were secondary and determinism was the correct metaphysical position, the role of unique individuals or contextual and historical detail could be safely ignored. Those areas of study such as the social sciences, where individuals and circumstances play a major role, were also thereby relegated to the realm of the 'subjective'. Accordingly, they did not qualify as sciences.

1 *Linearity.* In the modern perspective, moreover, causal relationships were assumed to be linear in two senses of the term. Small changes were assumed to produce only small effects and novelty was relegated to consisting only in the unfurling of previously hidden potentiality. That nothing absolutely new was possible also fit in nicely with the theological and religious context in which the seventeenth century European philosophers and scientists wrote. That mathematical equations describing second order, nonlinear relationships are not analytically solvable, contributed to their expulsion from the scientific worldview. These equations were labeled 'intractable' and dismissed from further consideration.
2 *Nothing can cause itself.* Causal relationships were also thought to be linear in a different sense. Following Aristotle, the belief that circular causality is impossible and that nothing can cause itself or self-organize, was a central tenet in the new worldview. As mentioned earlier, and following a principle of Aristotle's which modernity did not discard (not the least of which because it meshed with these other assumptions) any form of self-cause was also forbidden. Since wholes were no different from aggregates, the idea that particles could interact to produce wholes with global properties that are truly novel and cannot be predicted from its components was thought to be nonsensical; the corresponding idea that global structures might loop back down and modify or otherwise alter their components was similarly scoffed at and top-down causation was thereby discarded. In organization theory, management and labor were thought to be two separate entities, with the former forcefully exacting change from the latter. The idea that the two groups could be viewed as one organization interacting reflexively with itself would have violated any accepted notions of causality, implying as it would have that something could change itself.

EXPLANATION

A particular logic of explanation corresponded to this approach. At the same time as he insisted that formal deduction from universal premises was the appropriate logic of explanation proper to science only (episteme), Aristotle maintained that because human beings are temporally and contextually embedded, episteme cannot be used to explain their behavior. Instead, practical wisdom (phronesis), which varies 'as the occasion requires' must be utilized in any satisfactory explanation of human affairs. Narrative thus becomes the appropriate logic of explanation in the domain of human activity. In contrast to this dual approach to understanding, the scientific revolution of the seventeenth century brought with it a particular interpretation of how explanation must proceed: solely by deduction. After David Hume's demotion of causality to an inductive habit and the generalized suspicion of inductive reasoning as problematic, philosophers and scientists concluded that logical derivation from timeless and contextless laws is the ideal not only of the natural sciences but of any legitimate reasoning process. Any law – not just a generalization, but a universal law supporting counterfactuals – when combined with statements specifying the initial conditions – must warrant the logical deduction of whatever is being explained. By the middle of the twentieth century, such a 'covering-law model' was the standard format into which all forms of explanation must be formulated.

INCLUDING PEOPLE AND THEIR ORGANIZATIONS

In consequence, every effort of the 'special sciences' turned towards reshaping their disciplines into scientific and therefore respectable enterprises. Merely descriptive narratives were disparaged. From Comte in sociology to Freud in psychology, the search for universal scientific laws covering social interaction or the human mind – and the possibility of deductive proofs derived therefrom – brought with it the inexorable mathematization of each of those disciplines. Even when deterministic algorithms were not forthcoming, social scientists continued to maintain that mathematics was the indisputable language of nature. We saw this progression most especially in economics; but even the newly burgeoning sciences of sociology, psychology, and anthropology – now often grouped together as the 'social sciences' – sought a reputation as 'sciences' precisely in light of their scholarly efforts to couch explanations in scientifically acceptable format. W. Edwards Deming's application of statistical controls to production is a later illustration of applying a mechanistic conceptual framework to management.

There had been early warning signals about the limits of this model prior to the twentieth century. Newton himself was well aware of what we now know as 'the three body problem' – that linear causal relationships go haywire once three bodies are involved. That nonlinear second-order equations describing such relations are not formally solvable also posed a challenge to the dominant paradigm of analytic reductionism. Newton's followers, however, continued to maintain that causality was exclusively a deterministic, one-to-one event of forceful collisions. Given one cause, only one effect follows, and it follows inexorably, thereby underwriting a deductive logic of explanation, not to mention prediction and control. But despite Newton's reservations, this mechanical interpretation of Aristotelian efficient causation continued to inform our modern view of cause and effect relationships for centuries, a framework that considered systems, societies and wholes to be nothing more than the aggregate or average of their component parts, and devoid of internal top-down causal power.

During most of the twentieth century and in accordance with this scientific paradigm, business managers and corporate executives during most of the twentieth century adopted these same assumptions, methods, and goals, all of which were thought to be assured, for example, by time and motion studies and well-crafted organizational flow charts. Making an organization emulate a well-oiled machine ensured that administrative and managerial interventions would increase efficiency and productivity. Although mention of the benefits of division of labor appear as far back as Plato's Republic, and had been implemented in Henry Ford's assembly line, the approach became known as 'scientific management' with the publication of Francis Taylor's *The Principles of Scientific Management* (1911). The application of seventeenth century science and philosophy in business and organization held out the promise of a new industrial age. From Frederick Winslow Taylor and Frank Bunker Gilbreth to Edwards Deming and Peter Drucker, management and organization theorists thus followed a path analogous to that of Comte in sociology and Freud in psychology as theories about the logic of explanation also made inroads into discussions about the kind of explanations best suited to organizations and businesses.

In addition to Newton himself, one of his followers, Immanuel Kant, was another doubter of the universality of mechanical causality. Even though this form of causality is the only account warranted by the so-called categories of the Understanding, explanations in terms of forceful collisions often failed when applied to living things, Kant realized. Thus in the *Third Critique of Judgement*, Kant wonders about the causality operating, for example, in trees. We find here, he says, a 'form of causality unknown to us,' a circular form of self-cause wherein the tree both produces the leaves and is produced by them. By identifying intrinsic goal-directedness with a circular type of self-organization, Kant reintroduced teleology and purpose into philosophy (Juarrero-Roque, 1985). But the entrenched Newtonian framework led him to limit the notions of self-organization, circular causality, and purposiveness to the realm of epistemology, not ontology.

Later on in the nineteenth century two additional challenges to the standard understanding of causality appeared. First the inexorable increase in entropy postulated by the second law of thermodynamics returned time to nature by identifying a universal and irreversible arrow of time: everything moves from order to disorder. At the same time as classical thermodynamics postulated the deterministically predictable and inevitable heat death of the universe, however, this new science posed a different challenge to reductionism and atomistic ontology: because properties such as temperature and pressure are emergent insofar as they apply only to the overall system, and are described in statistical laws that apply at the global level. The apparent contradiction of the reversibility of Newton's equations was also starkly problematic, but rethinking the entire paradigm was postponed when Ludwig Boltzmann appeared to reconcile mechanics and thermodynamics by arguing that the apparent irreversibility of the latter was due only to the statistical averaging of large numbers, as was the apparent emergence of novel properties. At the level of ontological bedrock, scientists continued to maintain that the equations governing the motion of fundamental particles, described exclusively in terms of their essential properties, remained reversible.

Additional anomalies soon appeared. On the face of it, biology and even cosmological evolution contradict the second law. Whence the increasing complexity and order-creation so much in evidence in development and evolution, both biological and cosmological? In opposition to both reductionism and the relentless heat death predicted by classical thermodynamics, Charles Darwin's theory of evolution, particularly its concept of selection, appeared to account for the increasing complexity and order we find in the living world; in Darwin's notion of natural selection, too, context was given a causal role to play for the first time in centuries. And to make matters even more complicated, the strict determinism of classical mechanics appeared to break down as a result of the self-organizing consequences of a spiraling reflexive causality. Darwin himself, however, believed that his accounts, although correct, did not offer a respectably scientific 'explanation' precisely because of their lack of deductive character. Given that chance and randomness were supposed to play at best only a minor role with respect to secondary, not essential characteristics, Darwin was at a loss as to how to incorporate random mutations into the received view of causality and explanation. One easily forgets the etymology of 'evolution: the unfolding of pre-existing potentialities'. Nevertheless, with the Darwinian theory of evolution and despite Darwin's own reservations came a renewed appreciation of the role both randomness and the environment play in causing qualitatively emergent, not just developmental changes in the realm of biology.

What went largely unnoticed in the nineteenth century was the fact that although classical thermodynamics reintroduces the arrow of time, it deals in systems that are closed, isolated, and near equilibrium, and that are temporal but not historical: despite their origins they march relentlessly towards increased disorder and disintegration. As dramatic evidence to the contrary, open, far from equilibrium systems such as individual organisms and organizations – whether beehives or international corporations – become increasingly complex and individuated over time before senescence sets in, and they carry their history and the context in which they are embedded in their very structures. Since history plays an essential role in all living things, including human beings, it is unsurprising that their behavior, and the organizations they form and in which they play a part, did not yield well to a treatment that did not truly embed organisms in their environment or took their history into account. The new science of ecology highlighted the inadequacy of the classical model. The Lotke–Volterra equations, for example, showed that rather than tending towards a final unitary state of equilibrium, predator–prey relationships oscillate back and forth from one steady state to another. The one-way, one on one determinism assumed to hold everywhere in nature was under attack.

The pendulum began to swing definitively against the established paradigm with the articulation of general systems theory by organismic biologist Ludwig von Bertalanffy (1968). The fundamental claim of the systems perspective is that iterated feedback causes properties to emerge and become integrated into an orderly context, novel properties that are absent when things exist in isolated or relative independence from each other. In an aggregate, the properties of the parts do not alter depending on whether or not they are part of the aggregate, but in a system, the properties of the components depend on the systemic context within which the components are embedded. Dynamic correlation and coordination among parts cause the emergence of new properties in living systems and organizations. The dynamic integration of parts into an orderly whole makes it function more like an 'organic unity' than a machine or a clock. A strong echo of Aristotle's concept of formal cause reappears in the concept of a system.

In the last quarter of the twentieth century, a new branch of thermodynamics dealing specifically with systems that exchange matter and energy with their environment and that are far from equilibrium also began receiving increased attention. Often going by the appellation 'complex adaptive systems theory', or 'complexity theory', several key concepts of this new approach are better suited to historical, contextually embedded processes such as those pertaining to human beings and their organizations than is the mechanistic model. Complex systems are characterized by a peculiar circular causality whereby the product of the process is necessary for the process itself. Interactions among dynamical processes create systems with new properties that are not the aggregate or sums of the components that comprise the global level. Contrary to Aristotle, this type of positive feedback is a type of self-cause. Moreover, when hierarchical complexification occurs, multiple realizability becomes the norm: the higher level system can be instantiated in different token arrays. And predictability soon becomes impossible when even small perturbations affect the system at a crucial moment. Unlike their near equilibrium counterparts, far from equilibrium systems are exquisitely sensitive to initial conditions, which is another way of saying that small differences, nudges or blips can cause major, unpredictable changes. Within a few iterations, the behavior of two systems that are in practice indistinguishable from each other at the start will radically diverge, which makes the trajectory of all complex systems *de facto* impossible to predict and therefore totally control.

When parts interact to produce a higher-level organization and the resulting global – but distributed – structure in turn affects the behavior of the parts that make it up, inter-level causality is in play. Far from being inert epiphenomena that modern science claims all wholes are, complex dynamical structures exert active power on their parts so that the overall system remains dynamically robust. This regulatory control preserves the organization's integrated system of values – its invariant relations – that give the global system its identity. Despite significant variability at the component level, the higher level is thus able to maintain itself in a meta-stable dynamic equilibrium robust to perturbations.

Complex dynamical structures also regulate and constrain the lower level parts that constitute them, but not forcefully, as efficient causes. These causal relationships have recently been explained as context-sensitive or context-dependent constraints or conditional probability distributions (Juarrero, 1999). In particular, efforts to reformulate formal and final cause have used the self-organization of dissipative structures as the theory-constitutive metaphor around which to reconceptualize causality in general, this time in terms of the context-sensitive constraints responsible for the differentiation and complexification characteristic of both organic development and evolution. Contextual constraints make complex dynamical systems more than the sum of their parts and therefore different from and irreducible to their aggregation. A complex system's contextual constraints also control its components top-down by altering, for example, their natural frequency and thereby restricting their phase space.

In organization theory, the human relations movement of the second quarter of the twentieth century, and the more recent emphasis on group dynamics, team building, and the like, were early attempts to incorporate non-mechanistic principles into management practices once the drawbacks of that approach were recognized. Replacing technical experts with behavioral scientists in organizations and firms reflected this conceptual change as well.

As the interactions and nonlinearities at work in open systems became better understood, these new ideas, many of which are now gathered under the rubric 'complexity theory,' forced the rethinking of many of the general assumptions underlying the classical model of causality entrenched in the natural and social sciences, including organization management. With the rise of complex science it suddenly became respectable to question the notion of linear causality supporting determinism and exact predictability, particularly with respect to living things, as Kant had anticipated. The discovery of a world not of random chaos but of an intricate, higher level order has been nothing short of revolutionary.

Complex systems became more tractable with the reintroduction of the Aristotelian concepts of formal and final cause by making it easier to account for the contextual embeddedness and goal-directedness of organisms and organizations. Accordingly, complexity scientists applying its concepts to organization theory have noted the significance of Aristotle's four causes to our ability to understand, if not predict, the workings of firms and other types of human organizations. Bill McKelvey in particular explicitly adapted the four Aristotelian causes to the context of organizations, and offered a new understanding of their complex causal interactions in that domain.

According to the received mechanistic model of explanation, a phenomenon was considered fully explained only when it could be inferred from a covering law together with initial conditions, and thereby predicted. Although causes and effects cannot be the same in all respects, traditional views of causality also assumed that similar causes, under similar conditions, always produce similar results. The nonlinearity of positive feedback and circular causality present in complex systems vitiates these two assumptions. As a result, a different logic of explanation becomes necessary. When nonlinear interactions cause interlevel relationships like those described above, the meaning of individual events can be understood only in context: in terms of the higher-level constraints (the dynamics) that govern them. Those higher-level constraints, in turn, are produced by the very interactions occurring at the lower, particulate level. The logic of explanation of hermeneutic narrative and story telling is therefore more appropriate for phenomena whose very nature is a product of the strange causal circle between whole and part, with feedback tentacles reaching out into the environment and back in time. In the business and organizational world, David Snowden applied these insights to develop a series of techniques based on the use of storytelling and narratives as an advanced knowledge depository to track tacit knowledge in organizations and firms.

The recognition that precisely because of the tangled causal networks in which complex systems are embedded and with which they co-evolve dynamical, adaptive systems are not predictable in detail the way planetary motions are has had a profound effect on management and organization theory. How are we to explain and understand a phenomenon other than by capturing its essence in an equation, then plugging in the variables describing the situation being studied so as to be able, through deduction, to predict and anticipate its future course? Fortunately, in the last half of the twentieth century the computing power of personal computers allowed researchers to simulate the second-order nonlinear differential equations that were analytically intractable but which captured the behavior of phenomena as diverse as chaotic turbulence and population dynamics.

Changes in our concept of explanation made parallel appearances in management books as business theorists began to incorporate this cognitive framework. Knowledge management theorists were quick to recognize the significance of the shift in the logic of explanation. Because of the role time and context play in complex systems, attempting to explain complex systems deductively is otiose. In management and organization studies, early attempts to incorporate history and environmental context can be found in the Total Quality Management's (TQM) emphasis on life cycle issues. Max Boisot and Ian MacMillan (2004) used agent-based modeling to track knowledge flows within and between organizations to the learning strategies of organizational players.

It was not until the advent of complex adaptive systems theory that the notions of stability and resilience were properly disentangled and their causal links explained. Resilience, in ecological terms, was described as the ability to adapt and survive despite serious shocks and perturbations. Some very stable systems, it was discovered, were not at all robust or resilient. When perturbed beyond a particular threshold, they quickly perished. It also became clear that when evolution selects for resilience, not stability.

Ralph Stacey was among the earlier authors on business management to recognize both the pervasive influence that the mechanistic model in general and the billiard-ball understanding of causality in particular had on organizational theory. In a series of books beginning with *Complexity and Management*, Stacey (2001) addressed issues of complexity in organizations. In particular, Stacey emphasizes the distributive nature of complex systems, including organizations, especially the distributive property of the latter's knowledge assets. Whereas in its early years, management theory aimed at controlling individuals, tasks, and actions, once the interrelationships among tasks and roles were recognized, organizational theory then focused on managing and controlling those so-called tacit knowledge relationships, which included organizational culture and values. The increasing importance given to intellectual capital gave rise to various theories concerning Knowledge Management. In particular, knowledge was first thought to reside either in the employees' minds or in the organization's explicit procedures. Once Baumard application of Michael Polanyi's notion of tacit knowledge to organizations was published (Baumard, 1999), Stacey carried the implications of understanding that knowledge as a distributed and participative, self-organizing process to its logical conclusions. As such it can neither be stored, measured, nor managed. So how is a manager to manage?

Systems whose components are tightly connected often possess a high degree of integration relative to the disintegrating perturbations entering from their surroundings. However, at times, the cohesion of the system's subsystems can challenge the preeminence of the global system. Coordination, on the other hand, is a different, functional phenomenon: if coordination among the components fails, the system undergoes functional breakdown. A complex machine out of kilter is a good example of the latter. If we ask, What are the causes of resilience and stability? How is resilience enhanced? What makes complex dynamical systems different is the fact that their components are interrelated with each other and are embedded in their environment through feedback loops. Stability is usually inversely related to integration: the more flexible the coupling between the subsystems the more stable the overall system. Usually too, the more homogeneous and stable the environment in which the system is located, the more stable the system. Resilient systems are flexible and nimble, capable of modifying their specific structure to ensure the adaptability and survival of their overall organization. Complex systems are usually more resilient than simple ones, with complex open systems that interact with their environment exhibiting the highest degree of resilience. It is now known that the more diverse the component types and the greater the variety and number of internal couplings the higher a system's resilience will be. In recent years, research into these kinds of causal links and pioneered by Peter M. Allen's (1988, 1990) group at Cranfield University in the UK, showed that microdiversity is the engine that propels a species's fitness. The implications for management and organizational theory are clear, and have already been widely adopted in business. Notably, business and military leaders have been at the forefront with respect to the issue of affirmative action in their organizations: both sectors recognized the need for a diverse workforce and military in promoting successes in a globalized world.

The implications this new way of looking at causality holds for business managers and organizational leaders are evident: no matter how precisely organizational functions and roles were compartmentalized, the very nonlinear dynamics that integrate them inevitably also cause major, unpredictable and uncontrollable change, a good example of which is the financial crisis that began in 2007. And since tacit knowledge is distributed, the best managers can aim for is to ensure that the business is organized dynamically in such a way as to be as resilient as possible. Doing so will provide the organization with the agility to self-organize at crisis points. The role of any manager and, leader, therefore, is more like that of a catalyst than a clockmaker, a fact that requires managers and other business leaders to abandon the ideal of stability and change and adopt resilience as a goal in its stead (Juarrero-Roque, 1991; Stacey, 2001).

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10

Complexity and Limits to Knowledge: The Importance of Uncertainty

Peter Allen and Jean Boulton

INTRODUCTION

This chapter examines how complexity science faces up to the material fact of uncertainty and the very real limits to knowledge. Indeed it shows how ignorance, the impossibility of having full knowledge and the inevitability of uncertainty, are both the result of, and the driving force behind, evolution and change. The chapter will review how this affects the exploration of complex problems and in particular the approaches to the mathematical modelling of their embedded but often un-defined limitations. This involves examining the assumptions that are necessary in order to represent a 'situation' in terms of changes in the values of a particular set of variables and the ways this whole structure moves forwards over time. Our feeling of 'understanding' seems to correspond to the degree of predictability such methods imply, since we feel that we do not 'understand' a situation when we are unable to predict future behaviour. This definition of 'understanding' is questionable, however, since it assumes that the future already exists within the present and that it can therefore be determined. But this does not allow for learning, adaptation, change, exploration or creativity of any kind. In short it corresponds to an assumption of the stability and fixity of:

- the initial system – the mechanisms that link the variables
- the internal responses inside each individual element
- the system's environment

In other words we 'understand' things by assuming that they will continue to do what they are doing; we pay less attention to how, why or when they came to be like this, and to what they may do, individually and collectively, in the future.

In addition to this great simplification that assumes fixity and unchanging behaviour, often a further assumption is made of dynamic 'equilibrium' whereby even the trajectory of the system of fixed mechanisms is supposed to have run itself to a stationary state, independent of the particular history or movements that actually took place. So we assume that it is generally appropriate and possible to understand most situations through investigating a static end point rather than by exploring how things change. Clearly this is an even-more-unlikely assumption than believing in fixed, deterministic dynamics; but nevertheless this idea has been dominant in economics, creating a false impression of certainty and of the existence of a deterministic relationship between the state of a market and the external conditions in which it sits.

Complexity, and indeed the presence of coupling and feedback between interacting elements, shows the limits of these simplifying assumptions. The sources of uncertainty are manyfold-:

- Uncertainty in the behaviour of individual elements inside the system
- Uncertainty in the collective behaviour of the system
- Uncertainty in the way the system interacts with other systems
- Uncertainty in the boundaries of what we define as a system or systems
- Uncertainty in the environment in which the system is immersed and the way the system responds to changes in this
- Uncertainty in how any description of elements, systems or the environment may change over time

We argue that, in the real world, uncertainty is a real experience and 'exists'; and this embracing of uncertainty is the fundamental underpinning of complexity science. It is the science that arises when the questionable, even incredible, simplifications that lead to assumptions of determinism and prediction cannot be made.

In this chapter we explore the ontology of uncertainty, from ancient cosmologies through Darwin to Prigogine and the beginnings of complexity theory. We then transfer our interest to the epistemological questions as to how you explore, or indeed ignore, uncertainty. We take an overview of ways of exploring complex problems, focusing in particular on mathematical modelling; we look at how uncertainty is handled or ignored or even denied through the use of various simplifying assumptions.

We then move our focus more specifically to human systems and take the example of economics; we consider how uncertainty has been considered, historically, in the field of economics. Finally, we present an example of the impact of including uncertainty in an evolutionary model of a market.

THE HISTORICAL ROOTS OF UNCERTAINTY

The pre-Socratics and 'becoming'

Our current dominant worldview which underpins most mainstream schools of thought in economics, policy-making, management, education and development still centres on the mechanistic idea that the world is objective, measurable, predictable and controllable and that is despite almost overwhelming evidence to the contrary. Uncertainty has not had a place in this view, apart from as a limiting irritation, to be overcome by increasing knowledge and greater scholarship. Has this always been the case? Early philosophers in both the East and West held a much more sophisticated position: they have seen the world as changing and flowing, but yet with a degree of order and patterning that arose intrinsically, from within.

This image of flow and change is captured in the following fragment, part of the few remaining writings of Heraclitus (Kirk et al., 1957).

> Upon those that step into the same rivers different and different waters flow … They scatter and … gather … come together … and flow away … approach and depart.

The Hindu Upanishads and the Dao de Jing present a similar sense of temporary patterning emerging without the need for extrinsic design or planning.

And Democritus (Monod, 1970) said:

> Everything existing in the universe is the result of chance and of necessity.

Plato, however, refused to believe that form or patterning could arise without external design and introduced the idea of a Creator who, guided by pre-existent perfect forms, created a world, which emulated and aspired to them. Uncertainty and fluctuations were seen as irritating limitations and something to be overcome; they were not seen to serve any useful purpose.

This theme of perfection and order then paved the way for the seizing of Newton's mechanics, in the seventeenth century, by French Enlightenment thinkers and became *the* dominant world view; where order, prediction and control are regarded as attainable and desirable and variation is viewed both as a nuisance and largely irrelevant. How did this happen? Why was Newton's theory of physics, which in fact applied, merely, to certain limited problems of interaction between discrete objects, seized on as *the* dominant worldview? Many authors (for example Toulmin, 2001) have written on this topic at length. In summary, Newtonian thinking supports the notion of 'the grand design', and of the view that logic and reason will lead to the 'right' answer; indeed it implies there *is* a predictable 'right' way and 'right' answer. So it represents a way, a rationale, to control chaos, to be efficient, to overcome superstition, to make things happen in a predictable fashion; this is very beguiling.

Darwin and variation

In contrast to this view of achievable perfection, stands the messy and inefficient and surprising process of evolution. It was Darwin (1859) who recognised that uncertainty is indeed *necessary* for change to happen. Whilst the realisation that animals and plants evolve had been recognised for decades before Darwin's expedition on the *Beagle*, indeed by his own grandfather (Darwin, 1794), Darwin's contribution was to suggest that variation was a fundamental part of how this happened.

Charles Darwin wrote (1978: 169):

> In 1838 … I happened to read for amusement Malthus on Population, and being well prepared to appreciate the struggle for existence which everywhere goes on …, it at once struck me that … favourable variations would tend to be preserved, and unfavourable ones to be destroyed. The results of this would be the formation of new species.

The notion of messiness as playing a useful role, *fundamental* to innovation, adaptability and change, is very significant. Despite its seeming acceptance there is still much resistance to its implications as evidenced by the continued focus on prediction, design, control, measurement and an endless search for certainty.

The idea that variation is a pre-requisite for evolution and change to happen was a Big Idea that subsequently captured the imagination of philosophers, psychologists, sociologists – and eventually physical and biological scientists. For example, the Pragmatist Charles Peirce (1955) was one of the first to recognise the wider implications of evolution as a worldview. In 1891, he wrote:

> Now the only possible way of accounting for the laws of nature and the uniformity in general is to suppose them results of evolution. This supposes them not to be absolute, not to be obeyed precisely. It makes an element of indeterminacy, spontaneity, or absolute chance in nature.

Equally, William James (1995) explains in 1884:

> Of two alternative futures which we conceive, both may now be really possible; and the one become impossible only at the very moment when the other excludes it by becoming real itself. … To that view, actualities seem to float in a wider sea of possibilities out of which they are chosen; and, ***somewhere***, indeterminism says, such possibilities exist, and form a part of truth.

So, the early philosophers noticed the world changed in an uncertain way but nevertheless had form; Darwin recognized that variation and uncertainty were in fact *central* to the emergence of new form; it was the physicist Prigogine (1947) who took the next step. He started to explore *how* uncertainty led to emergence and evolution, and how the future is *in principle* unknowable. This was the beginning of the new science of Complexity.

Prigogine's early insights into the relationship between function and variation

Prigogine (1997), in his autobiography, tells us that, in his adolescence, Henri Bergson's (1911) book 'L'évolution créatrice' cast a spell on him. Bergson posed the question as to why, if physics, in the form of the second law of thermodynamics, proposes that matter and form degrades into structureless dust, does life mount the incline that matter descends (Bergson, 1911: 245). He focused on the image of the universe as 'becoming' rather than 'being' and recognized that *what is real is the continual change of form: form is only a snapshot view of a transition* (Bergson, 1911: 301).

Prigogine's initial interest was in non-equilibrium thermodynamics and led to considerations of how patterns in certain chemical and hydrodynamic systems open to the environment came to emerge. He was inspired by the work of Bénard (Jantsch, 1980), a French physicist who discovered patterns of convection cells in a liquid layer when heat is applied from below, and through the experiments of two fellow Russians, Belousov and Zhabotinsky (Jantsch, 1980), who discovered, in a particular mix of chemicals, that the colour of the mix oscillated between yellow and clear. Alan Turing (1950) was also making similar discoveries.

Prigogine (1947, 1996) is perhaps best remembered for these explorations of non-equilibrium thermodynamics. His subsequent work (Prigogine, 1978), showed that the emergence of patterns (later called self-organization) came from the inter-relationship of the *function* of the underlying process together with *fluctuations*. Monod (1970) explores a similar theme in his book, *Chance and Necessity* though he assumes that the chance of creative events is small whereas Prigogine took such events to be inevitable and frequent. By *function*, Prigogine was referring to the underlying internal dynamics; in an ecology, for example, this would define what drove the 'rules' of interactions; who can eat whom, what food intakes are typical, how long it takes for mature fish to grow and so on. He also underlined the fact that the particular history of a particular ecology or market or chemical system depends on the particularity of chance events or variations. This complex, systemic view introduces 'history' into science (Prigogine, 1978). It implies that most situations cannot entirely be understood through mathematical equations defining universal laws.

As an example, if we consider a pond, and consider the density of pondweed, the temperature of the water, the size, age and type of fish, the size of the ripples on the water, such factors will not be uniform over the pond or with time. Furthermore, if we ignore these variations, we run the risk of throwing out the very information that determines future states. It is this fine-graining, which Allen (1997) termed micro-diversity, that is fundamental to the potential for self-organization, self-regulation, the potential for emergence of radically new qualities and forms and for the fact that the future *is under perpetual construction* (Prigogine, 1997: 1). Prigogine emphasized that fluctuations *play an essential role* (1978: 781) and affect the direction the system subsequently follows. As Jantsch (1980: 6) states:

> a system now appears as a set of coherent, evolving, interactive processes which *temporarily* manifest in globally stable structures.

This combination of coherent behaviour and yet random variation gives the tension between 'chance and necessity', between 'uncertainty and prediction'. Chance fluctuations give the system its unique history and yet the movements take place in the context of coherent dynamics which are stable, at least for a time. As Allen (1997: 16) explains:

> [this] begins to throw light on the basic difference thought to exist between 'science' and 'history'. In the former, explanation was believed to be traceable to the working of eternal, natural laws, while the latter provided explanation on the basis of 'events'. In this perspective of self-organising systems we see that both aspects are present and that such systems are not described adequately by either laws (their internal dynamics) or events (fluctuations) but by their interplay.

THE DEVELOPMENT OF COMPLEXITY SCIENCE

Hiding complexity

Following the early insights into complexity and the importance of non-average events and non-average types, we can situate the many different ways that the real complexity of the world is hidden in contingent, closed and simplified representations. This is shown in Figure 10.1 which illustrates the different types of representation and mathematical models that arise from successive assumptions about stability within and outside the system.

Figure 10.1 represents, starting from 'reality' on the left, which is full of uncertainty and doubt, and, making successive assumptions about the piece of 'reality' under study, one passes from complete uncertainty, through various intermediate views to one of complete deterministic certainty when prediction is believed possible. We will look at these in turn to see how the actual complexity and uncertainty of 'reality' is hidden from view and tools and models are developed that appear to offer control and knowledge to those that possess them. In essence the things that make prediction 'possible' are closure to outside influences and fixity within.

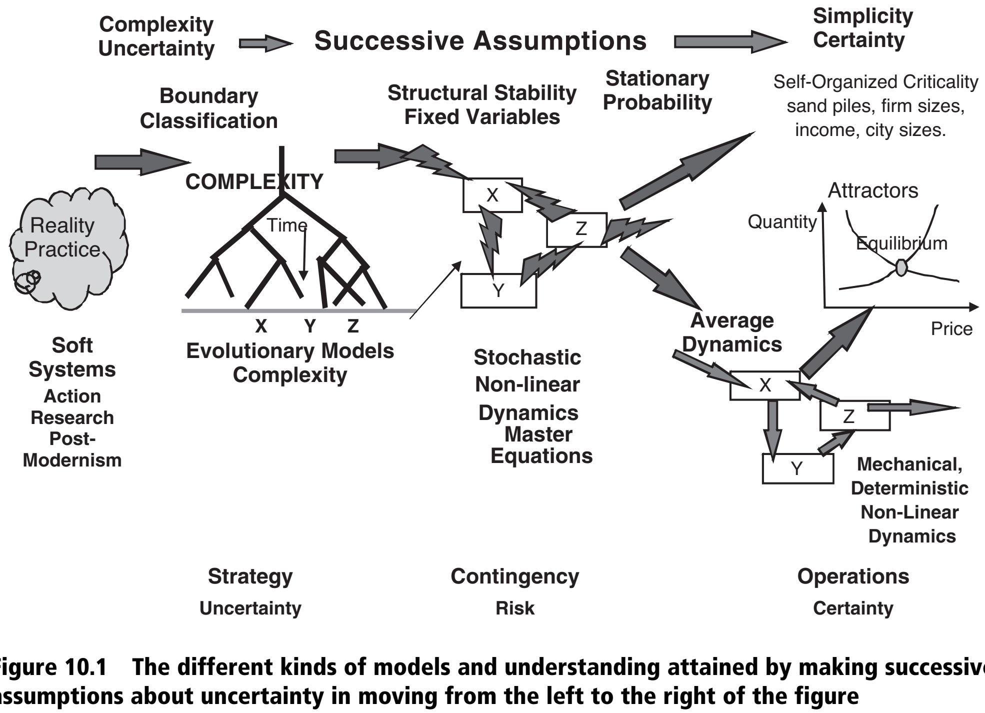

Figure 10.1 The different kinds of models and understanding attained by making successive assumptions about uncertainty in moving from the left to the right of the figure

'Reality'

One can argue that we need make no assumptions and should just engage with 'reality'. Whilst we can interact with particular situations and contexts in 'real life', it is impossible, in general, to work in this way as the amount of information required to look at every detail, every nuance, is prohibitive. Lyotard (1984), in *The Postmodern Condition* gives the example of an emperor wishing to make a perfectly accurate map of his empire; the project leads the country to ruin as the entire population is needed to devote all its energy to cartography.

But, on the other hand, neither can we argue that problems have stable outcomes and are open to abstraction. Quoting Lyotard (1984) again: *the continuous differentiable function is losing its pre-eminence as a paradigm of knowledge and prediction.* So what is to be done? Figure 10.1 shows us how, in scientific models, understanding and prediction are achieved in practice by making successive assumptions concerning the situation under study. On the left-hand side, where no assumptions have been made, there are no established types, variables or equations. We are in the realm of literary and historical endeavour, where we are describing and perhaps responding to what is happening, but are limited in our ability to learn or generalize or predict. It is the realm of postmodernism, of action research and of many anthropological methods where we are reminded that any generalizations are likely to be misleading. Emphasis is placed on staying with the actual experience of what is, on focusing on the particularity of an actual, living situation and working with all the variation and all the uncertainty that is present.

Such heuristic methods are indeed very important and stop us from blindly applying, and indeed uncritically accepting, models and theories. However, we would argue that modelling plays its part as an aid to exploring complex problems and we are interested here in critiquing differing approaches to modelling and understanding their differing assumptions.

Evolutionary complex models

The first assumption, in moving away from 'raw reality', is to say that there is a 'boundary' and that some things will be considered to be inside and others will be outside, in the environment; even this assumption must be handled carefully as boundaries may shift or may be permeable and any assertions or selections regarding boundaries will typically be open to the criticism that they are assumed or constructed. However, modelling allows us to explore and test such assumptions and understand the sensitivity to such choices.

The second assumption concerns that of 'classification' in which we decide to label the different types of thing that populate our system. This might be biological species and perhaps their age cohorts, or, in social systems, people classified according to their ethnicity or philosophical beliefs, or their skills or professional activities; so in this way we specify the variables of the system.

What happens if we make only these two simplifying assumptions but still work with nonlinear interactions and feedback and allow 'noise' or variation in the system? We are in the realm of evolutionary complex models. In Figure 10.2 we see the results of a computer run in a 200 × 200 character space in which we study the populations over time where we have reproduction, exploration (mutation) into neighbouring character cells, and both synergy and competition for resources for any particular type. What we find is the creation over time (time is downwards) of a simple ecology of populations (Corliss et al., 1990).

In this approach, we find that over time the constituent types may change. New types and activities emerge and others leave. Over time qualitative evolution occurs and the system is not structurally stable in that the variables and therefore the equations describing the mechanisms and processes at

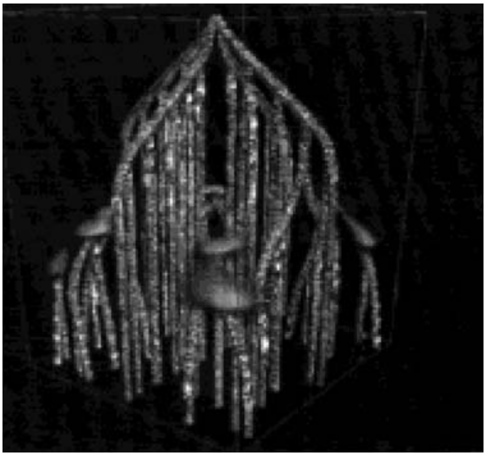

Figure 10.2 The emergence of a simple ecology over time for a population diffusing in a 200 × 200 character space. Each population has synergy and competition for resources

work within it can change; there are a series of instabilities as new things emerge and others disappear.

Variations both determine which possible outcomes emerge and furthermore they shape the future possible dynamics. In other words, the microscopic variability and randomness in the system drive evolution, confer on the system the ability to learn and hence to adapt and in so doing impact on the environment which co-evolves with it. There is no way that we can exclude 'luck' from the evolution and changes that occur in the system, and there is no way that we can banish uncertainty from our considerations.

Probabilistic dynamics; The Master Equation

With only two assumptions (boundary and classification) we see that the general evolutionary model shows us that qualitative change will occur, that new qualities will emerge and others disappear; but cannot say exactly in what way or when. What happens if we make a further assumption that the dynamics, the basic interaction mechanisms that govern the situation cannot change, but we still allow fluctuations and non-linearities?

Prigogine had established the central and creative role of variation and fluctuations in creating the future. Prigogine (Nicolis and Prigogine, 1977; Prigogine et al., 1977) and also Haken (1978) wanted to understand *the way* in which fluctuations play their part. Traditionally there were two distinct methods of exploring how a number of elements interacted. If there were a small number of elements, then it was possible (at least in principle) to track the movement and interaction of each element. In contrast to this *dynamical, mechanical method*, if there were large numbers of elements, then *statistical mechanics* was used and the behaviour of the system was treated essentially as if it were a fluid and average qualities such as density or temperature, were tracked; elements were classified into categories and were assumed to be identical and unchanging and, most importantly, only the most probable events were assumed to occur. In both cases, generally, only first-order effects were calculated; so the interaction of any two elements in the dynamical case were assumed not to be affected by the presence of other elements; and in both cases interactions were assumed not to be influenced by previous interactions. These two methods, basic mechanics and statistical mechanics, sit off to the right of the processes shown in Figure 10.1; they are 'off the map' in terms of their simplicity and their inability to deal with complex interactions and change.

Dynamical systems are deterministic but are sometimes very sensitive to initial conditions (when the parameters correspond to a 'chaotic' attractor); probabilistic systems are also deterministic but are largely *independent* of initial conditions and move towards equilibrium. How then do these two methods relate to each other and how can either method make sense of the role of fluctuations and the propensity for self-organization and multiple possible outcomes?

Progress was made to resolve this dilemma through the use of the so-called 'Master Equation' that governs the dynamics of a probability distribution (Allen, 1988). This method allows one to work with *all possible sequences of events,* taking into account their relative probability, rather than just assume the most probable events occur, as would happen using 'normal' statistics. The collection of all possible dynamical paths is taken into account in a probabilistic way. But for any single system this allows into our scientific understanding the vital notion of 'freedom' or 'luck' or 'uncertainty' in the behaviour of the system. Although, a system that is initially not at the peak of probability will *more probably* move towards the peak, it can perfectly well move the other way; it just happens to be *less probable* that it will. A large burst of good or bad luck can therefore take any one system far from the most probable average, and it is precisely this constant movement that probes the stability of the most probable state. It also points us towards the very important idea that the 'average' for a system should be calculated from the distribution of its *actual* possible behaviour, not that the distribution of its behaviour should be calculated assuming the average is fixed.

Allen (1988), in the first instance, investigated a simple grazing predator–prey system of two species; both species can reproduce and die. Traditional statistical mechanics would assume equilibrium and give an average outcome corresponding to a balance of numbers between the two species, depending on the food resources available. However, working with less simplification through using the Master Equation, Allen shows that for some conditions the probability distribution moves from whatever its initial condition is towards a distribution with two distinct peaks of probability. The first corresponds to the extinction of both species and the second to a stable balance between them. In other words, when the individual events that underlie the mechanisms are treated probabilistically, allowing for different possible sequences of events according to their probability, the state of the system demonstrates path-dependence, moving to one or other of the possible stable configurations. We see also that the word 'outcome', which seems so innocuous, really hides an assumption of equilibrium, of having got to where it must go. But with nonlinearities in the interactions the system may have several different possible configurations to which it could 'go'.

This simple example was very important. It shows how, if qualities are averaged as in 'normal' statistical methods, the very detail that determines the path of the system is lost; that is to say a bifurcation occurs. It shows that working only with the most likely 'outcomes', as with statistical mechanics, can be *qualitatively* misleading. So, the use of the Master Equation shows us the importance of the actual history of a particular real situation. Can we know which outcome would have happened in practice in the 'real' world? What would have tipped the system into one direction rather than the other? Or could both outcomes occur simultaneously in different places?

Stationary probability; solving the dynamic equations

The dynamic equations of probability that we have described in the last section are quite difficult to handle, involving correlated probabilities of interacting variables and so further assumptions are often used to make the problem simpler. There is a choice; either we can adopt a traditional scientific approach and try to 'solve' the dynamic equations to find their stationary solution; or we can decide to retain only the dynamics that results from the most probable events and follow the path that unfolds. This second approach, the dynamical systems approach, we will explore in the next section.

The first of these methods, 'solving' the dynamic equations to find their stationary solution, leads to particular probability distribution functions shaped by the mechanisms contained in the Master Equation and gives a view of the final probability distribution to which, it is assumed, the problem has settled. For particularly simple mechanisms such as a 'sand pile' to which grains are continually being added (Bak, 1997) the probability of an avalanche of a given size can be calculated. These ideas have been applied to many different systems such as the probability of earthquakes, city sizes and firm sizes. The distribution of probability is often that of a 'power-law' that describes the probability of different-sized events. For instance, it might suggest that the probability of finding a city or firm twice the size of another is only one quarter, i.e. it follows an inverse square law. If this pattern holds for cities or firms of all sizes, then the distribution is said to be 'scale free' (Bak, 1997).

We would question this approach on two counts. First, how often, in practice, do we find data that corresponds to this kind of stationary, stable, scale-invariant distribution? For city and firm sizes the data over time tells us that there is still a great deal of dynamic change occurring, as cities and firms grow and decline (Batty, 2008). We may wish to assume stationarity, but even within a stationary probability distribution, there can still be considerable underlying changes occurring. In the spectrum of automobile manufacturers for example, Toyota recently replaced GM as the largest company, but recent problems may lead to further re-ordering in the distribution. And how can we decide whether the variations occurring at any given moment are simply fluctuations within the stationary probability distribution or instead reveal a changing distribution? For example, in considering climate change it is very difficult to tell whether some 'freak weather' event is simply an extreme event within the pre-existing distribution or is in fact an indicator of a change in the distribution. It is very difficult from the data to decide whether the assumption of stationarity is justified.

Second, when nonlinear terms are present in the interactions between elements we know that different possible 'attractors' can exist and the corresponding probability functions will be multi-modal (have different peaks corresponding to different possible solutions) and not tend to a single peak, a single stable outcome. Clearly, where there are multiple equilibria, the shape of the probability distribution will be described by much more complex mathematical functions than a power law, x^{-a}, since it will have to describe several different peaks of probability. This is the situation we considered in the previous section as exemplified by the grazing predator–prey model.

Dynamical systems

If instead of asking 'what will actually happen to *this* system?', that requires us to deal with all possible system trajectories according to their probability, we ask 'what will *most probably* happen?' then we have a much simpler approach. We proceed by assuming that only the most probable events occur; that things happen at their average rates. This leads us into 'system dynamics' which is in general a nonlinear set of dynamical equations that appear to be predictive and deterministic. In other words, they seem to allow the future trajectory of the system to be calculated. Such an approach would seem to provide a basis for policy and strategy analysis by comparing the differences made over time by investigating the impact of one intervention as opposed to another, that is, by running the model several times using different assumptions. This is a very tempting picture for any decision or policy maker. It appears to offer a way to test different decisions and allow their advantages and disadvantages to be compared.

In situations where not much is changing in the broader environment or indeed within the system itself, then system dynamics models may well provide a good representation of system behaviour. They can show the probable effects of a particular intervention, assuming that no structural changes are provoked. They can also show the factors to which the system is potentially very sensitive or insensitive, and this can provide useful information. But systems dynamics models are still deterministic; they still only allow for one solution or path from a particular starting point. It is the path into the future traced by average elements interacting through average events, and is only reasonable if non-average elements and non-average events have no systemic effect; that is to say there is no self-organization or learning for example. Such systems can function but not evolve.

Risk, uncertainty and prediction

The important point that we need to reflect on is that such apparent powers of prediction, as implicit in deterministic models, is only real if, and only if the assumptions made in achieving it are in fact true. In other words the real uncertainty that may characterize the long-term evolution of an ecology, economy, market or firm is only banished by assumption. In this light therefore, we must admit that understanding and predictions will only hold until things change and our expectations are confounded. Our methods therefore do not scientifically eradicate the uncertainty of an evolving world, but instead mask it and tell us that providing the system doesn't change then we can predict what it will do. But clearly the uncertainty is now as to whether the system will change or not.

While it may be reasonable to believe that the system may hold its structure for short times, this becomes increasingly unlikely for longer times, since history has shown us that over longer time periods everything of interest seems to change as new entities and types appear in the system and others become extinct.

What indeed is uncertainty? We would argue, along with Knight (1921), that uncertainty is defined as that which cannot be known, as an 'unknown unknown'; it is associated with the underlying structures and constructs themselves shifting, or disappearing and new ones appearing.

This is something more than risk. Risk refers to situations in which the variables and mechanisms are known as well as the dimensions of the model and its environment, and signifies the case where these do not change. So stochastic nonlinear dynamics allow us to investigate risk, or known unknowns, but only evolutionary models allow us to consider true uncertainty.

COMPLEXITY AND UNCERTAINTY IN HUMAN SYSTEMS

The evolution of complex, resilient natural systems is linked to the retention of mechanisms of adaptability within them and reflects an underlying lack of specific purpose. Human beings, on the other hand, want to improve, direct or control systems for some particular end and because of this tend to eliminate any apparently unnecessary parts and to streamline operations. This leads to vulnerability, however, because though the system may operate better for a particular purpose it lacks alternative mechanisms that may be needed if circumstances changed. For example, the potential for growth and diversity of any society or city depends to an extent on the imagination of its people. But ideas cannot be produced by dictat, according to some rational plan. They depend on a population's diversity and originality of thought; on its individual freedom and ability to experiment; and on the finer details of its history, culture and social interactions. Generally speaking, microscopic diversity resulting from the mixing of cultures and diverse doctrines will be an important ingredient for a population's survival, although nearly all rational planning aims at minimizing such 'inefficient' eclecticism.

In this chapter we cannot look at the way complexity and uncertainty are handled over the whole breadth of social systems. We will, however, look at one example, that of economics.

Limits to knowledge in economics

Introduction

Complexity thinking has influenced the emergence of evolutionary economics (Nelson and Winter, 1982; Metcalfe, 2007), ecological economics (Boulding, 1950, 1981; Georgescu-Roegen, 1971; Daly, 1999; Costanza et al., 2007), behavioural economics (Simon, 1955) and complexity economics itself (Beinhocker, 2007). However, it is a self-evident truth and perhaps never more self-evident than in current times that there is a huge uncertainty in how any particular economic policy will play out in practice. For example, the neo-liberal policies of the last several years have been predicated on the view that market forces, if left largely free, give the 'best' chance of 'success' and that regulation should be kept to a minimum; but 'best' in what respect, and success for whom? It appears that, whilst growth has been substantial, the divide between the incomes of the rich and the poor with this reliance on market forces has significantly increased (Harvey, 2005) and there has been a general tendency for diversity and consumer choice to reduce with markets increasingly dominated by decreasing numbers of increasingly large players.

Equally, the deregulation of the money markets has led to a sort of pyramid selling, with a consequent collapse. And of course we are now, more than ever before, facing the question as to whether some natural resources are running out, whether population growth will overtake the ability of the land to feed it, whether climate change will rend many parts of the globe too hot or too dry or too drowned for human use. How can economics deal with these factors?

Perhaps what is most concerning about economic policies is that the system in question, the global economic system, is hugely complex and full of uncertainties; we cannot assume the rationality and consistency of actors, nor that they act with all the information they need; we cannot assume that the past is a good predictor of the future; we cannot assume stability; we cannot assume simple cause-and-effect relationships and be certain what causes what. This is hardly a surprise, yet the methods and assumptions of neo-classical economics still largely prevail. And on top of this, we cannot really isolate economic decisions from issues of social justice, the environment, security and the longer-term.

Equilibrium

How is uncertainty viewed within economics? Traditional neo-classical economics parallels and indeed borrows the assumptions embedded within the physics of equilibrium thermodynamics and implicitly assumes the economy is not far from equilibrium and that the mechanisms that influence it can be described as simple, linear, causal relationships. Any uncertainty or variety or learning or historicity or the possibility of multiple and reflexive inter-relationships are largely ignored within the models. Change is largely treated as an optimizing move towards equilibrium. If such a statistical approach were positioned on the diagram in Figure 10.1, such an approach in fact sits to the right of the models described due to the restrictiveness of its assumptions.

Why *should* things find balance or move towards equilibrium? Economists have borrowed equilibrium theory from the natural sciences. But in physics this is based on the behaviour of certain types of closed systems and reflects the conservation of mass, energy and momentum at the microscopic level of molecular collisions. Is the transfer of this mathematical framework valid when modelling the economy, and is there evidence to support this approach? This attribution of science is very compelling. The economist Leon Walras, in 'Elements of Pure Economics' written in 1874 is unequivocal in asserting its validity. He says: *this pure theory of* *economics is a science which resembles the physico-mathematical sciences in every respect.*

Social theorist Thorstein Veblen, as early as 1898, challenged these assumptions in his paper, *Why is Economics* not *an Evolutionary Science?* In this he points out that assuming the economy moves towards equilibrium or balance is a teleological argument; that is to say, it is assuming a pre-ordained end point to which things naturally move. Why should there be such an end point?

Veblen in fact, argued that to see the economy as evolutionary, constantly shifting as variations and new things challenge the status quo, is a much more rational perspective. Complexity economist Brian Arthur (1994) recognized that, to assume a move towards equilibrium, one had to assume that negative feedback loops prevail in economic relationships, leading to the notion of perfect competition based on supply and demand balanced by price; but there is no reason to suppose that this always prevails. Arthur points out that in many circumstances, positive feedback or increasing returns is the norm, and competition can be affected by small events and choices which 'lock-in' certain solutions and where successful firms keep growing at the expense of the competition.

Arrow (1994), points out that this insight was not new, but has surfaced every decade or two, throughout the history of economics, starting with Cournot in 1838. The idea that there are in practice multiple potential and temporary points of stability has been well-aired in economic literature.

Economic Man

As well as assumptions about the underlying dynamics of the economy, neo-classical economic approaches need to assume, for ease of calculation, that consumers act rationally, in the sense that Economic Man makes consistent, rational, easily analysable choices typical of his 'type'; furthermore, competition is deemed to drive the economic process; competition is regarded as 'perfect' in the sense that it is undertaken with full and perfect information available to all the players and that it plays itself out to completion.

The nature of Economic Man's rationality is taken to mean that his decisions are about satisfying his own, and largely immediate, needs in a cost-effective manner. As Frank Knight (1921) points out:

> economic man … is postulated as knowing definitely and accurately all the facts and magnitudes, knowledge of which would influence his behaviour. … The economic subject would in many cases have to have perfect foreknowledge as well as perfect knowledge.

In reality, Alan Greenspan (2008), reminds us that: *the innate human responses that result in swings between euphoria and fear repeat themselves generation after generation with little evidence of a learning curve.*

Risk and uncertainty in economics

The fact that the economic landscape is uncertain and risky is not a new thought. Frank Knight (1921) made his famous distinction between 'risk' (randomness with knowable probabilities) and 'uncertainty' (randomness with unknowable probabilities). Keynes (1937) reflected similarly:

> By 'uncertain' knowledge …, I do not mean merely to distinguish what is known for certain from what is only probable. The game of roulette is not subject, in this sense, to uncertainty … The sense in which I am using the term is that in which the prospect of a European war is uncertain, or the price of copper and the rate of interest twenty years hence … About these matters there is no scientific basis on which to form any calculable probability whatever. We simply do not know.

The sociologist Zygmunt Bauman, reflecting on what he calls the current 'liquid times' (2007) postulates that uncertainty and fast change are defining features of our age. He says that:

> social forms (structures that limit individual choices, institutions that guard repetition of routines, patterns of acceptable standards) can no longer

> (and are not expected) to keep their shape for long, because they decompose and melt faster than the time it takes to cast them, and, once they are cast, for them to set.

Uncertainty, in economics, has, perhaps, generally been considered a limitation; something to aim to diminish through risk assessments or standardisation. In contrast evolutionary and complexity thinking suggest that a level of variation and messiness is *necessary* for adaptability and development as we have already discussed. Nowotny et al. (2001), for example, say:

> The inherent generation of uncertainties in both science and society is one of the crucial elements in their co-evolution.

And, indeed Shackle (1958) also recognized the generative quality of uncertainty. He said:

> the word uncertainty suggests an objectively-existing future about which we lack knowledge rather than [more positively] a void to fill with new creation.

So uncertainty is not a new thought to economists; the difficulty is, of course, that if the economist accepts uncertainty in its entirety then he is limited in what he can do to try and advise on how to predict or to control the future. So the economist makes do, perhaps, with deterministic models because, otherwise, he is limited in what he can achieve.

This is not to say that economists have not developed approaches which, in terms of the range of models shown within Figure 10.1 do not move us towards the left of the diagram, more towards uncertainty and the messiness of the real world. The field of evolutionary and complexity economics is increasingly well-developed (e.g. Foster and Metcalfe, 2001; Witt, 2008).

Alan Greenspan (2003) states: *Uncertainty is not just an important feature of the monetary policy landscape; it is* the defining characteristic *of that landscape*, and (Greenspan, 2003) states: *Our problem is not the complexity of our models but the far greater complexity of a world economy whose underlying linkages appear to be in a continual state of flux.*

Modelling market evolution

Instead of simply assuming that a market is populated with decision makers having perfect information and knowledge the complexity view leads us to consider the more realistic situation in which investors, managers and consumers have very incomplete and imperfect knowledge about what will happen and in which we do not imagine that there is only one possible outcome. They are trying to learn and to adapt according to outcomes, in line with the notions of exploration and exploitation described in March's (1991) classic paper.

Allen et al. (2007) have developed models that explore the likely probabilities of success where firms adopt not just different particular strategies (price/quality) but different *meta*-strategies. For example, these may be: (a) a strategy of incremental learning, (b) a strategy of imitating the strongest competitor, and (c) an intuitive, entrepreneurial strategy represented in the simulations by choosing 'randomly'. These meta-strategies are related to those discussed by March (2006) in his paper entitled 'Rationality, Foolishness and Adaptive Intelligence'. In the case of Allen et al. (2007) the meta-strategies of incremental learning and of imitation of the current winner represent different forms of rationality, while the entrepreneurs are 'foolish'. The paper explores the relative effectiveness of these different approaches, as well as their interdependences.

Allen et al.'s (2007) model tests the benefits or otherwise of 'learning' as a meta-strategy, which is important because if 'random strategies' were found to work better, there would be no point in studying, or in obtaining and analysing sales and market data; we could simply rely on our intuitive powers, or flip a coin, to decide what strategy to adopt. This relates to Schumpeter's (1939) important ideas about creative destruction; Schumpeter makes no real comment on whether firms can actually improve their survival rates as a result of internal processes. Instead, it is really the introduction of new firms that will have randomly better or worse technologies and internal structures that shapes the evolution of the market. Ormerod (2005), similarly, shows how it appears from the data that firms do not in fact learn.

In building a model such as Allen et al. describe, the modeller is confronted with the problem of what knowledge and uncertainty an agent can sensibly be assumed to have concerning the sales and revenue generation that will result from a given strategy. If no firm ever went bankrupt then we might make the mistake of thinking that considerable knowledge was present. However, an examination of the statistics concerning firm failures (Foster and Kaplan, 2001; Ormerod, 2005) shows that, whatever it is that entrepreneurs or firms believe, they are clearly, often completely wrong. The bankruptcies, failure rates and life expectancies of firms all attest to the fact that the beliefs of the founders, managers or investors are often not correct. Clearly, what really happens is that agents adopt, and probably believe in, particular initial strategies relating to product, quality and price, and the marketplace is then the theatre of learning in which some of them discover that their meta-strategy *does* take them on a successful trajectory, and others discover that it does not.

For the mathematics of such a model, see Allen et al. (2007).

The model generates a market evolution as goods or services are produced and consumed. The revenues from the sales of a firm are used to pay the fixed and variable costs of production, and any profit can be used either to increase production or to decrease the bank debt if there is any (see Figure 10.3).

All bankrupt firms are 're-launched' into the simulation with a randomly chosen strategy, but they retain their identity as learner, imitator or entrepreneur, so that there are always six of each kind competing in the system. The program runs a simulation with random initial strategies (quality and choice of mark-up), and replacements dependent on a random sequence of numbers; 'seeds' are used so that particular random starting points can be reproduced.

Results

Summarizing the results of multiple simulations for different random sequences (seeds 1 to 10) then we find the overall results of Figure 10.4. The message from this is clear. Learning by experiment is the best meta-strategy. Adopting entrepreneurial randomness is good, and imitating winners is the least successful meta-strategy.

It is indeed interesting that entrepreneurs really do better than might be expected; in addition provide exploratory behaviour of use to the rest of the system. This finding rather supports the remark made by March (2006): *Survival may also be served by the heroism of fools and the blindness of true believers. Their imperviousness to feedback is both the despair of adaptive intelligence and conceivably its salvation.*

Allen et al. (2007) also studied the spread of results obtained by all the different 'learning' curves and this showed that the results are robust.

Allen et al. (2007) concluded that, although in general 'learning' is better than 'not learning' the spread of the results shows that in any particular case this may turn out not to be true. This suggests that, even if a player owned the simulation model, it would still not be possible to use it to predict the exact strategy and meta-strategy to use in order to be sure of 'winning', because the strategy choices that will be made by other firms, represented in the simulation by the particular random sequence selected, cannot be known at any particular moment (Allen et al., 2006).

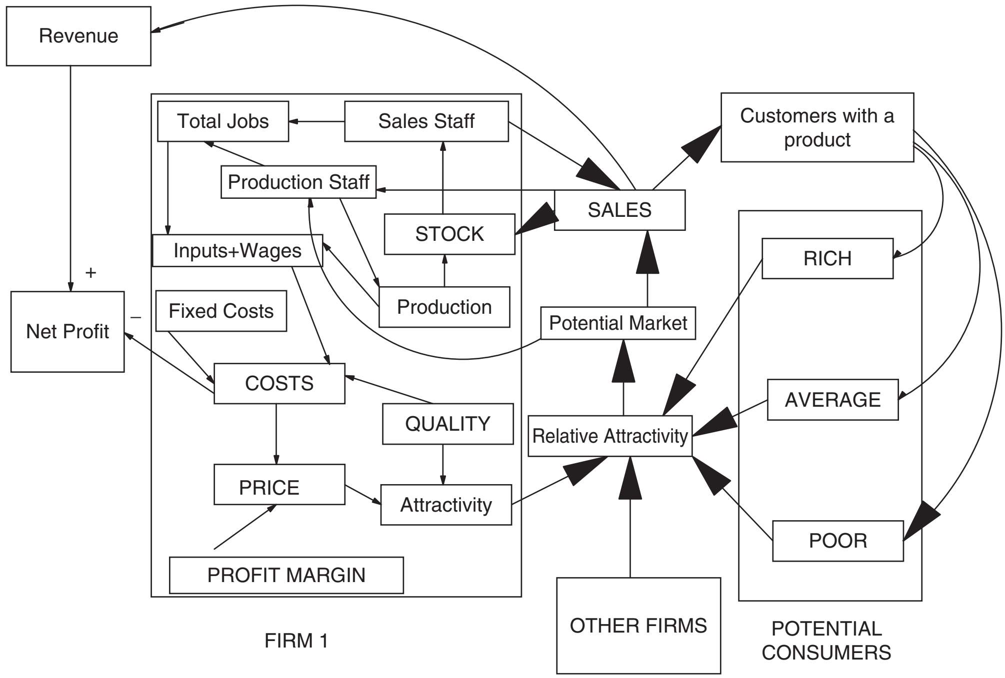

Figure 10.3 The evolutionary market model

Of course, over time, evolution will occur and new technologies, innovations, organizational changes would change the parameters, the mechanisms and the behaviours of the agents involved, as with full-blown evolutionary models. Over longer times, it is necessary to widen the perspective of the exploration and try to discern whether or not the dynamical system is evolving qualitatively.

DISCUSSION

One important error that we need to expose is that after recognizing the shortcomings of 'classical science' in dealing with highly-connected real-world situations, we can simply turn to 'complexity science' to provide a set of 'tools' that can be applied to obtain prediction, control and the knowledge necessary to make decisions and policies. We have to recognize that prediction, control and complete understanding are always an illusion, except for exceptional, controlled, closed and fixed situations, usually in laboratories.

However, this does not mean that 'modelling' has no role to play in complex situations. On the contrary, the alternative to 'trying to build a model' is 'not trying to build one', which can require us to rely on the use of intuition and plain pragmatism instead. And, as Einstein said: *Intuition is the summation of prejudices acquired up to age eighteen.* Thinking itself is a form of modelling.

Faith and hope would mark such an 'intuitive' approach and the bankruptcy data tells us that, except for the very lucky, this is not an effective strategy. Pointing out the nature of the assumptions that need to hold for a particular type of model to be correct can help us to explore the behaviour of domains of linkage which, for some time, may be useful. In other words, complexity tells us that ultimately we are involved in pragmatism; but instead of simple intuitive pragmatism we can adopt a pragmatic approach to models and see them as experiments in

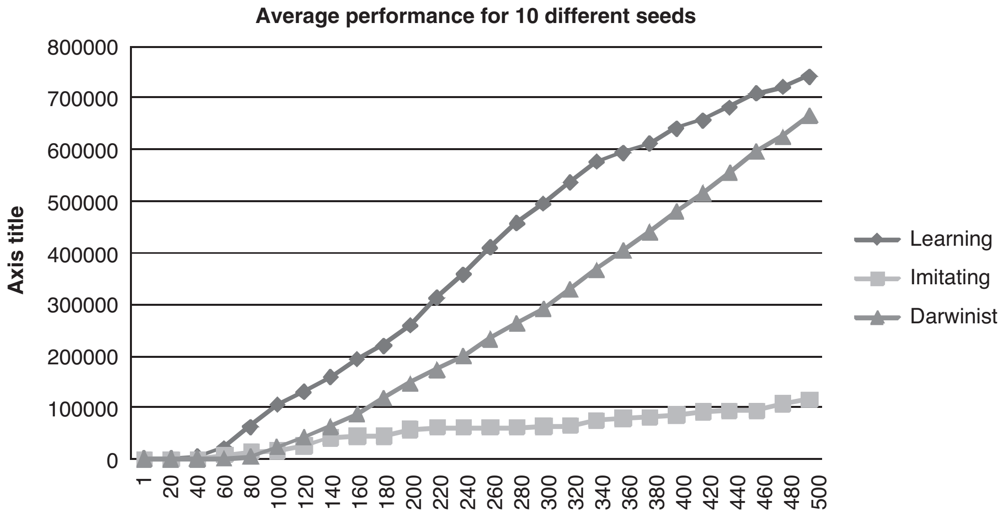

Figure 10.4 The average results for 10 random sequences, each with six firms of each type

representation, where we retain those that seem useful and continue to modify those that fail and treat all as an adjunct to thinking, not as defining 'the answer'.

We would argue that information about many technical systems cannot be obtained in any way other than by simulation. Where such simulation and modelling methods fail is often where human reactions and responses are included, and some simple rationality has been assumed. Humans are more complicated, more confused and more heterogeneous than that, and also they get bored, change, learn and imitate, often incorrectly. However, in dealing with many management issues there are production systems, logistical supply and distribution systems, collaboration, competition and changing market conditions. In order to 'manage to survive' it seems clear that trying to understand and perhaps 'model' the situation is advantageous, providing that any outcomes are not taken as the incontrovertible truth. As shown in the example in the section 'Complexity and uncertainty in human systems' it is on the whole better to try to 'learn' from experiments than not. Learning beats intuition or imitation on the whole. The learning that is possible is limited and needs to be constantly tested and re-worked on a constant basis. We can never sit back and say, 'that's it, I know how the system works and can simply continue like this'. The world, other agents, and technological possibilities will move on and whatever assumptions are contained in a particular representation will be found inadequate at some point.

This implies that we are destined and indeed evolved to live always with uncertainty. Certainty only arises for closed systems and correspondingly closed minds. But the real world, outside the laboratory, is not closed from outside connections or from internal heterogeneity and micro-diversity. Without uncertainty, we would argue that life would not be worth living, since all would be pre-determined. But evolution has fashioned us to face it and even enjoy it, while working all the time to try to reduce it through our actions of organizing, constructing and protecting. Uncertainty is one face of evolution and complexity, and our game is to try to counter it with actions and innovations that actually, whether we mean to or not, create new uncertainties as we go. This is a never-ending (we hope), multi-level game of creation and response that is far more appealing and interesting than the closed, controlled and predictable world that we may have believed was where science had led us. Uncertainty and complexity are therefore part of a modern, deeper, scientific understanding of the evolutionary processes in the universe.

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11

Complex Thinking: Towards an Oblique Strategy for Dealing with the Complex

Robert Chia

Complexity fascinates and confounds. At times it is reminiscent of that proverbial enigmatic, shadowy and elusive nocturnal creature that appears only fleetingly for us to catch a glimpse of before it disappears mysteriously back into the darkness and beyond. Despite its profound effect on virtually every aspect of modern life, full understanding and comprehension of complexity eludes us at every turn. Its reticence in revealing itself fully to our scholastic gaze may have something to do with our academic temperament and the nature of our investigative approach. In this chapter, I propose a more oblique and circuitous strategy for understanding and managing the complex: one in which, paradoxically, the act of detour allows better access to its hidden nature and inner workings. In other words, I suggest, we need to complexify our thinking in order to learn and better appreciate the nature of complexity. In this effort to complexify thought, this chapter resonates with the concerns raised by several other chapter contributions in this handbook including that of Shotter and Tsoukas and Kurt Richardson in seeking to wean our thought processes from the dominance of natural scientific thought on the nature of complexity. More specifically, it advocates learning from the arts the *art* of complex thinking for the arts have long explored and appreciated the subtleties, paradoxes and nuances associated with the human condition. It urges us to set aside our natural inclination to apprehend social phenomena 'head-on' by showing how in that very act of direct apprehension we unwittingly forfeit access to those very insights we so very much seek. Social and managerial complexity retreats into the shadows when directly confronted. They are best approached through stealth. We propose here an indirect strategy for gaining access to the phenomenon of complexity in social life and suggest their implications for management.

INTRODUCTION

> The difficulty of complex thought is that it must face messes … interconnectedness among phenomena, fogginess, uncertainty, contradiction. (Edgar Morin, *On Complexity*, 2008: 6)

The natural, social, economic and political worlds are increasingly characterized by instability, volatility and disruptive change. It is a world in which the improbable, the unanticipated and the downright catastrophic seem to occur with alarming regularity. Witness the shocking events of 9/11, the Asian Tsunami disaster of December 2004, the global financial crisis of 2008 precipitated by the collapse of the sub-prime mortgage sector in the United States, and the recent boldly-coordinated terrorist attack in Mumbai in November 2008. 'Black Swans' (Taleb, 2007), those outlier events that occur beyond the realms of regular expectation and that turn out to have dramatic consequences for our everyday lives, abound in virtually every aspect of society; from the natural to the political, the economic and the social. What we *do not know* or do not expect seems intent on thwarting our best laid plans and disrupting our everyday lives in innumerable ways. We are constantly forced to reassess our understanding of how the world works and how we may learn to adapt to and cope with the challenges we face as best as we can given the uncertainties we find ourselves in. In other words, it is a genuinely complex, multi-faceted and globally intertwined world that we live in today.

A complex world, however, calls for complex thinking: thinking that issues from the intimacy and immediacy of pure lived experience (James, 1912/1996: 23; Nishida, 1921/1990: 3; Ruskin, 1927, Vol. XV: 27; Morin, 1977/1992: 392–393); thinking that acknowledges and embraces the inherent messiness, contradictions and puzzling character of reality (James, 1911/1996: 50; Morin, 2008: 6); thinking that resists or overflows our familiar categories of thought (James, 1911/1996: 78–79; Whitehead, 1926/1985: 64; Bergson, 1946/1992: 161–162; Morin, 1977/1992: 393); and thinking that is sensitive to the suppressed/marginalized 'other' that is denied legitimacy in our dominant scheme of things (Marcuse, 1964: 144–147; Ehrenzweig, 1967: 38–39; Said, 1978: 2–9; Lacan, 1986: 203–207). It acknowledges that we must remain constantly alert to the taken-for-granted assumptions that continue to exert a vice-like grip on our habit of thought. Our thought, says Edgar Morin, 'must lay siege to the unthought which commands and controls it … *we need a principle of knowledge that not only respects but reveals the mysteries of things*' (Morin, 1977/1992: 16, emphasis original). It entails recognition that all forms of seeing and knowing involve the simultaneous act of foregrounding and backgrounding: that there is an inevitable blindness in seeing and an unac*knowledged* 'owing' in our 'kn-*owing*'. In directing our attention to the unthought, complex thinking heightens awareness of our ignorance. We must start by extinguishing false certainty, says Morin, setting out only in 'ignorance, uncertainty, confusion. … Uncertainty becomes viaticum; doubt of doubt gives doubt a new dimension, the dimension of reflexivity … the acceptance of confusion … becomes a means of resisting mutilating simplification' (Morin, 1977/1992: 10). This is the radical starting point for genuinely thinking complexity.

The rather paradoxical 'argument' that we make here is that complex thinking is better appreciated as a cultivated predisposition resulting from the gradual *complexifying* and subverting of efficiency-based habits of thought. In other words, a complex way of thinking is attained *indirectly* and 'inefficiently': obliqueness in approach is key to the apprehension of complexity. Complex thinking, as such, arises non-deliberately as a 'negative capability' (Keats, 1817); the ability to think complexly is an emergent outcome of sustained resistance to the dominant orthodoxy rather than a deliberately cultivated predisposition. The direct and instrumental approach to inquiry and knowledge acquisition that characterizes the scientific approach must, therefore, be set aside and an intellectual space or conceptual 'clearing' created for the pristine experiences of life to speak to us on their own terms and in their own time. Instead of confronting our objects of inquiry directly, we need to embrace more subtle strategies of engagement that acknowledge the primacy of the heterogeneous and multidimensional becoming of things, events and situations (Bergson, 1911; Whitehead, 1929; Prigogine, 1981). The nature and quality of emergence from the simple to the complex constitutes a multifaceted, intertwined and unfolding drama; an adventure into the unknown that unavoidably and simultaneously shapes our own futures and our sense of self. We show here how, in philosophy, the arts, literature and the humanities, this awareness of the value of complex relational thinking and the deficiencies associated with a simplifying, frontal approach in understanding and dealing with the world, has led to the development of a more nuanced set of 'suggestive' strategies for apprehending the complexities of social life. We end by exploring some implications of complex thinking and the indirect approach associated with it for understanding managerial action.

LEARNED IGNORANCE: ON COMPLEXITY AND INNOCENCE

> *Layman:* I am amazed at your pride because although in perusing countless books you tire yourself with continual reading, you have not yet been brought to a state of humility. … True knowledge makes one humble. …' (Nicholas of Cusa, *Idiota de sapienta*, 1450/1996: 497)

Socrates was wise because he was acutely aware of his ignorance and of how much effort it took to confront it. But as Allan Bloom (1987: 40–43) points out, 'Socrates only knew, after a lifetime of unceasing labour, that he was ignorant. Now every high school student knows that. How did it become so easy?' How indeed has it become possible for us to take our ignorance so lightly? How have we become so comfortable and blasé with knowing that we do not know? One possible answer lies in the fact that within conventionally established frameworks of understanding, ignorance is generally defined as a 'gap' in our knowledge; a technical problem, something that can be easily overcome or rectified through the incremental process of acquiring more knowledge or information. Socratic ignorance, however, is an ignorance that is acutely attuned to the background 'unthought' that circumscribes the thinkable and knowable. Socrates was acutely aware of what he did not know. He was always already the exemplary complex thinker acutely attuned to the possibility of *otherness*. The literary critic Barbara Johnson echoed this deeper insight on the importance of the unthought when she wrote most passionately: 'Ignorance, far more than knowledge, is what can never be taken for granted. If I perceive my ignorance as a gap in knowledge instead of an imperative that changes the very nature of what I think I know, then I do not truly experience my ignorance' (Johnson, 1989: 16). In other words, it is only when we become painfully aware that it is *ignorance of our ignorance,* and not simply a gap in knowledge, that prevents deep insights into the human condition, only then do we begin to glimpse that illusive realm of complex thinking that characterizes Socratic ignorance.

The fifteenth century German cleric Nicholas of Cusa (1440/1981) calls this enlightened state of reflexive awareness *learned ignorance.* It is a condition that recognizes the inherent limitations and hence fallibility of conceptual knowledge and draws us to the realization that the richness and complexity of social phenomena we apprehend must be allowed expression on their own terms rather than in terms of pre-established categories of thought that have been inspired by the imperatives of high modernism. In this spirit of learned ignorance we begin to appreciate more deeply that the modern consciousness has been shaped by a 'paradigm of simplification' (Morin, 1977/1992: 376); a reductionist impulse which elevates the abstract linear, the fixed, the atomistic, and the bounded. This paradigm of simplification 'disenchanted' and 'devastated' the universe 'tearing her secrets from Nature … Reduction and simplification, necessary to analysis, became the fundamental generators of research and explanation, hiding all that was not simplifiable … things became objective: inert, fixed … *bodies* always moved by exterior laws … Science is totally unconscious of the praxic, metaphysical, anthropocentric character of its vision … Doctor Jekyll does not he is Mr Hyde' (Morin, 1977/1992: 373–374).

As a result, we are not good at thinking process, movement, flux, or transformation *on their own terms*. Our instinctive conceptual skills favour the static, the separate and the self-contained. Taxonomies, hierarchies, systems, structures and isolatable agencies represent the instinctive vocabulary of institutionalized thought in its determined subordination of dynamic complexity, inextricable relationality and precarious emergence that is so characteristic of lived experiences. The 'blooming, buzzing confusion' (James, 1911/1996: 50) that is very much the reality of our lived experiences is denied conceptual legitimacy even as they overflow our conceptual apparatus with rampant disdain. Consequently, the kind of knowledge acquired through this paradigm of simplification 'is forever inadequate to the fullness of the reality to be known'. They are 'secondary formations, inadequate, and only ministerial … they falsify as well as omit' (James, 1911/1996: 78–79). What we are provided with, therefore, is a distorted and reductive view of reality; the kind of 'mutilating thinking' that causes us to miss much of what life as actively lived offers us. 'When you understand all about the sun and all about the atmosphere and all about the rotation of the earth' says the philosopher Alfred North Whitehead, 'you may still miss the radiance of the sunset' (Whitehead, 1926/1985: 248). In short, possession of such knowledge in no way assures an intimate appreciation of the richness of lived reality. Instead, it is a more intimate form of knowing that is inextricably associated with what we call here *complex thinking*; thinking that works relentlessly to exhaust itself of dependence on categories in order to open itself to re-discovering the innocence of lived experiences. It 'exhumes and reanimates the innocent questions that we have been trained to forget and despise … there are more affinities between complexity and innocence than between innocence and simplification' (Morin, 1977/1992: 392–393). But how have we come to take this paradigm of simplification, this systematic disenchantment of the world as the founding basis for our comprehension of social life? How have we come to develop and privilege strategies of engagement that have downplayed the importance of the innocuous, the vague, the peripheral and the innocent in our dealings with affairs of the world? The starting point is to examine a most self-evident epistemological stance underpinning both academic research and modern human action; the widespread belief in the superior efficacy of a direct, rational approach in dealing with social phenomena in order to render them more comprehensible and hence amenable to productive action.

THE DIRECT APPROACH IN HUMAN ENGAGEMENTS

> [i]n the Gaze, the painter arrests the flux of the phenomena, contemplates the visual field from a vantage-point outside the mobility of duration, in an eternal moment of disclosed presence … The Gaze is penetrating, piercing, fixing, objectifying. (Bryson, 1982: 94)

Within the still-dominant Western tradition of thought it is generally accepted that the way to understand and deal with both material and social phenomena is to directly apprehend them using the most efficient investigative tools and/or conceptual apparatus available to arrive at a thorough and comprehensive understanding of the latter. The natural instinct is to address that which interests us, differentiating it from that which does not, meticulously dissecting and reducing the isolated phenomenon under investigation to its component parts, and then proceeding to systematically represent each of these part-elements using pre-established concepts and categories. A closely-coupled causal explanation involving the identifying of a constant conjunction of precedent and antecedent events is then employed to produce a satisfactory and comprehensive account of the phenomenon under investigation. This sequence of analytical steps provides the basis for a rigorous form of scientific research that is by now familiar to most. Yet, it is this very analytical procedure of focused separation, reduction and abstraction that ultimately 'mutilates' and distorts that which we are seeking to comprehend. For Morin, the ontology of Western science has been 'founded on closed entities, such as substance, identity … causality, subject, object' etc. (Morin, 2008: 34). According to this substance ontology (Rescher, 1996: 27), processes, relations, and interactions are construed as epiphenomenal attributes of essentially self-identical entities. Commitment to this substance ontology entails prioritizing: substance over activity; discrete individuality over interactive relatedness; descriptive fixity over productive energy; and classificatory stability over fluidity and evanescence (Rescher, 1996: 31–35). What Rescher usefully clarifies and what Morin is alluding to is a whole tradition of Western thought since Aristotle which has been based on a metaphysical assumption regarding the unproblematic self-identity of things.

According to this Western tradition, something is not deemed real unless it is capable of enduring in time and hence is capable of being assigned an identity. Things, events and situations are believed to present themselves fully to us at any moment in time so much so that their meaning and significance is fully exhausted by the immediacy of their presence before us. We are deemed to have an unmediated access to meaning in all its totality without there being any hidden remainder. This metaphysical stance has been problematized by the German philosopher Martin Heidegger (1962) and labelled 'metaphysics of presence' by the French philosopher Jacques Derrida (1984) in his deconstruction of Western logocentrism. What Morin is alluding to and what Rescher has usefully clarified is this widespread reliance by Western thought in general and Western science in particular on such a 'metaphysics of presence' which treats substance, presentness, and self-identity as ontologically unproblematic. This unquestioning acceptance, in turn, encourages a confident direct approach in apprehending a phenomenon when attempting to understand and explain it. The methods of research and inquiry inspired by this intellectual predisposition are thus underwritten by the desire to gain direct and immediate access to that which we are attempting to comprehend. This is an approach which appears to work particularly well when dealing with relatively stable and unchanging physical entities. It is less effective when dealing with living systems such as biological entities and becomes highly questionable when addressing the more ephemeral realms of the social and the symbolic. Yet, these potential limitations have not discouraged sustained attempts to address issues in the social world with this approach developed primarily within the physical sciences.

Such directness of approach is deemed to be more efficient in the production of proper knowledge, more consistent with established scientific practices and ultimately more resonant with the progressive values of a modern democratic society where order, transparency and accountability are highly prized. Clarity, precision and parsimony are highly valued aspects of this dominant Western disposition well exemplified by 'Occam's razor' and widely employed as guiding principles in scientific investigations as well as for dealing with the world of human affairs. The clamour for clarity in any programme of action, decisiveness in implementation, and immediacy in the attainment of results is everywhere present in the functioning of modern society and in particular in the world of business. Witness the ever-widening demand for focus, transparency, control, accountability and evidence-based practice as well as the almost-obsessive use of statistics and league tables in virtually every domain of social, economic and political life to aid rapid decision-making. The underlying Western disposition, whether it be addressing issues in science, politics, society or business remains one of direct, frontal engagement with identified issues and problems in order to assure their expedient resolution. But where has this penchant for approaching directly and decisively in the realm of human affairs come from and what are its wider consequences for our understanding of the human condition? One possible explanation comes from a study of the history of warfare in the West.

ADVOCATING THE VIRTUES OF DIRECT ENGAGEMENT IN WARFARE AND PUBLIC AFFAIRS

> [w]hat might appear pure carnage in this frontal clash corresponds to a principle of economy. (Jullien, 2000: 41)

The ancient military scholar Victor Davis Hanson maintains that there is much evidence to suggest that this preference for and advocacy of the virtues of direct engagement and confrontation in human affairs is traceable to a decisive shift in the manner in which warfare was conducted in ancient Greece after about the period beginning from the seventh century BC. For Hanson, it was the ancient Greeks during this period who first insisted on the superiority of a face-to-face frontal clash between opposing armies as the most appropriate way to do battle. Henceforth, a new structure, the *phalanx*, was introduced in which two bodies of heavily armed and cuirassed hoplites were made to advance in tight formation towards the enemy with no possibility of fleeing from a direct head-on confrontation with the latter. This frontal spectacular clashing of opposing forces represented a mode of engagement deemed most laudable in the practice of warfare. To win by any other means such as through harassment, evasion, ambushes or skirmishes was to 'allow … one side to "cheat" in a victory achieved by some means other than their own bravery in battle' (Hanson, 1989: 224). Skill in strategic manoeuvres and the use of cunning and deceit were rejected in favour of the supreme display of courage exhibited at the crucial moment of encounter. Heroic and spectacular engagements and interventions became the preferred *modus operandi* first in warfare and then subsequently in dealing with human affairs.

François Jullien (2000: 44) notes that a certain irresistible homology exists between the form of strategic engagement employed on the battlefield and that in theatre of social life. The 'face-to-face confrontation of the phalanxes on the battlefield (has) an equivalent in the face-to-face oratory and debate characteristic of modern democracies'. What is ubiquitous to the latter is its receptivity and willingness to embrace open dissent, public confrontation and debate and the employment of the art of disputation as the founding basis for societal progress. For Jullien, this '*agonistic* structure of confrontation' exists 'whether in the dramatic, the judicial, or the political realm' (ibid.). Hence, if a homology exists between warfare and public performances it is because both share the same confrontational *habitus* or predisposition (Bourdieu, 1990) as their preferred mode of engagement; one that leads to the valorizing of agency, intentionality, decisiveness, immediacy and spectacular outcomes; it is a practice that is ennobled by the language of radical discontinuities, revelations and revolutions. Victory is accomplished in triumphal terms.

> This figure of confrontation highlights the structure of the *antagonistic* thrust. Once two lists enumerating the advantages of the two sides of an argument have been established like two opposing phalanxes one settles the question merely 'by saying which list is longer or present greater advantage' … it is always by *surplus* – of arguments presented, not of secret obliqueness – that a victory is won. (Jullien, 2000: 47)

This penchant for dramatic, spectacular actions and interventions may be found in virtually every walk of life in the West particularly in the United States and, increasingly, with its vast reach and global influence, in virtually every other part of the world. From the glitz and glitter of presidential campaigns to the high drama of reality television, the glamour and hero-worshipping of movie stars and sporting super-heroes, to the insatiable appetite for eye-catching and attention-grabbing marketing stunts and ultimately, in the world of business, to the irresistible tendency to lionize successful corporations and captains of industry for their impressive short-term achievements; all these are symptomatic of a deeply-entrenched adulation for the dramatic within the realm of human affairs. The natural attitude of the democratic West, born of this ancient legacy, therefore, has been to eulogize transparency of intention, openness of competition, and the direct and heroic mobilization of available resources and capabilities to spectacularly achieve a widely publicized end. Yet, such directness in approach, both in dealing with human affairs and in human inquiry, carries with it inevitable downsides.

THE DOWNSIDE OF DIRECT APPREHENSION

> [u]like with action, which is always 'one-off', transformation affects the concerned collection of elements at every point … transformation is 'without locale'. Not only is it not local, as action is, but it is impossible to localize … its effects are diffuse, all-pervading, never limited. (Jullien, 2004: 57)

In his detailed comparison between spectacular action and silent transformation, Jullien (2004: 46) suggests that there are significant downsides to the direct approach in apprehending and dealing with phenomena. This is why, unlike many of their Western counterparts, ancient Chinese military strategists advocated relying on the natural 'propensity of things' to bring about social and political transformations. Avoiding confrontation and 'going with the flow' is almost second-nature to Orientals. In all forms of direct engagement, the explicit aim is the immediate overpowering and subjugating of an adversary, be it an enemy, a competitor, an object of inquiry or even passive nature itself. In warfare for instance, the aim is the annihilation of the enemy, while in a free market situation, business strategy is directed at eliminating or overcoming the threat of competition. Similarly, in research and inquiry, the object of investigation is treated in many ways like an adversary to be tamed, subdued and brought into the orderly fold of proper knowledge. In all three instances, this direct form of engagement results in the active *destruction* or 'mutilation' of the adversary in question. As an old Chinese saying goes, 'wherever he treads, the grass under his feet shrivels and dies'. Our insensitivity and clumsiness in directly approaching and handling the phenomenon of complexity frontally may well cost us that very comprehensive understanding we seek. But why exactly is it that direct frontal engagement often destroys? This is a question that must be explored in some depth.

Spectacular action is, by definition, external action that decisively intervenes and hence interrupts the natural course of things. It is as such unavoidably *intrusive*.

> Because it impinges from outside … by forcing itself into the course of things, it … tears at the tissue of things and upsets their coherence … (and) inevitably provokes elements of resistance, or at least of reticence … that … block and quietly undermine it. (Jullien, 2004: 54)

Moreover, such external intervention, because it intervenes at one moment and not another, tends to attract attention; it becomes a *spectacle* that forces itself onto our attention thereby becoming an 'event' to be accounted for. Its '*asperity* … provides a hook on which to hang a story' (Jullien, 2004: 55). Yet, despite its spectacular nature, it is more likened to a momentary 'shower of spray, against a silent background of things … The tension that it produces may well satisfy our need for drama … but it is not efficacious' (ibid.). In other words, direct, spectacular heroic and decisive action may provide us with drama and excitement but it is not necessarily the most efficacious or productive both in terms of deep learning and/or longer-lasting effectiveness. In contrast, a more oblique and circuitous form of engagement, because it harmonizes with the status quo and is perceived to be non-threatening, may surprisingly bear more productive fruit than the direct, frontal approach widely advocated. The efficacy of such an elliptical approach in apprehending and dealing with complexity is all the greater the more discreet and unnoticed it is.

APPROACHING COMPLEXITY OBLIQUELY: ANAMORPHOSIS AND COMPLEX THINKING

> … 'to point at the chicken to insult the dog' … the *obliquity* of the trajectory leads to a *depth* of meaning. (Jullien, 2000: 49–53)

Anamorphosis is an optics term which refers to a seemingly deformed and distorted image that only appears recognizable when viewed from a certain oblique angle. It is a visual cryptogram in which the image escapes immediate coherence when viewed frontally but becomes only comprehensible when viewed *obliquely* from a tangential point of view. In order to decipher the anamorphic configuration one must first relinquish one's dominant perspective and embrace a completely new perceptual vantage point so as to lose the 'obviousness' of what one sees in order to discover its new sense. The etymology of the word derives from a combination of two Greek terms "ana" meaning 'turning back', and "morphosis" meaning 'a shaping'.

One of the most well-known illustrations of this unusual feature in art which has caused much controversy in terms of its interpretation, is Han Holbein's *The Ambassadors* painted in 1533. In showing the portraits of Jean de Dinteville and Georges de Selves, prominent figures at the court of Henry VIII, amidst a plethora of Renaissance objects Holbein created a timeless masterpiece whose meaning and symbolism have been argued over for centuries now. The by-now familiar background objects in *The Ambassadors* – navigational instruments, a book of arithmetic, a lute, etc. – are drawn in a linear, frontal and single-pointed perspective bringing into focus the ambitions and achievements of Renaissance man. In contrast, the indistinct spot or elongated, oval-shaped blot that cuts diagonally across the lower half of the painting interrupting the spectacle presented draws attention to the limits of direct frontal vision. It is a blurred, seemingly incomprehensible smear. Viewed from an *oblique* angle rather than frontally, however, the blot turns out to be the distorted image of a human skull.

The classic interpretation of the skull is that it marks Holbein's ironic commentary on the *vanitas* of Renaissance science. The skull-blot in Holbein's painting signifies the fundamental antagonistic relation between frontal order and *obliquity*; that of the explicitly known and directly accessible and the tacit and unknown background upon which the achievements of the Renaissance are founded and sustained. The anamorphic figure of the skull renders explicit the limitations and one-sidedness of human vision and knowledge: we can either see the painting frontally or from the side but not both at the same time.

Anamorphosis reminds us that the direct, frontal apprehension and manipulation of reality has its limits: that there is an inevitable lack in all forms of knowledge gained through this direct mode of engagement; our forms of kn*owing*, for which direct apprehension and representations plays a central role, always implies a certain 'debt' or *owing* that can only be grasped obliquely rather than frontally. Contemplating the skull renders us more acutely aware of the outer limits of representational knowledge. Thus, for all its detailed attention on the material achievements of the Renaissance and the rational structure associated with it, arguably the true subject of *The Ambassadors* is paradoxically what is directly unknowable and/or unrepresentable. In this encounter with Holbein's anamorphic figuration, and the disruptive experience it provokes, complexity becomes fundamentally an existential experience of the sublime that issues from an immersed and prolonged engagement between the beholder and the beholden. Complexity is not merely an external phenomenon to be studied, understood and objectively applied in the resolution of problematic situations. Rather, it is fundamentally a subjectively felt disorienting experience involving the breaking down and blurring of categories, boundaries and distinctions; of that between the observer and the observed; of that between knowledge and action; and of that between identity and difference. In this regard, we are more aligned with Morin's insistence that 'complexity asserts itself first of all as an impossibility to simplify, it arises when … distinction and clarities in identities are lost, where disorder and uncertainty disturb phenomena, (and) where the subject/object surprises his own face in the object of his observation' (Morin, 1977/1992: 386). What this implies is that complexity is necessarily an acutely-experienced sense of the inadequacy of representation coinciding with 'the limits of our ability to comprehend' (Morin, 2008: 20). It is a humbling recognition and acceptance that there is no ultimate 'god's eye point of view' from which to comprehensively apprehend the world to affirm any presumed certainties and that each sense-making attempt and grasping action is no more than a tentative *wager*, an attempt to structure some much-needed coherence around ourselves so as to make life more meaningful and hence liveable.

THE MYSTERY OF COMPLEXITY AND THE VIRTUES OF VAGUENESS

> It is, in short, the reinstatement of the vague to its proper place in our mental life which I am so anxious to press on the attention. (William James, 'Stream of Thought', *Principles of Psychology*, 1890: 252–253)

The French existentialist philosopher Gabriel Marcel in his Gifford lectures delivered at the University of Aberdeen in 1949 and subsequently published in a book entitled *The Mystery of Being* (1951) makes a useful distinction between a 'problem' or 'puzzle' and a 'mystery'. Whilst a problem or puzzle can in principle be solved to some degree of satisfaction, a mystery can be illuminated through inquiry and investigation, yet despite such illumination the mystery is never ever dispersed. Each illumination only serves to further deepen the mystery. Problems are generally perceived as situations that are effectively detached from oneself and one's identity. I may choose to take up a problem, ignore it or circumvent it in order to get on with my life. A mystery, on the other hand, is a different thing. It gnaws at our being. How each of us confronts and responds to a mystery reveals who we are, what we think of ourselves and how we learn to cope with it. A mystery is unavoidably and inextricably intertwined with our own sense of identity. In seeking to resolve an irresolvable mystery, I am in effect embarking on an interminable quest to discover myself; seeking to forge my own destiny and self-identity. The questions who I am, why I am here and what am I to be, become inseparable from what I do. In this regard, whilst the solving of problems reflects our expertise, skill and competence, engagement with a mystery constitutes the passage towards self-discovery, self-cultivation and self-enlightenment.

It is just such an acknowledgement of the mysteries and complexities of life that animates the work of great artists, thinkers and poets, whose works are invitations to us to immerse ourselves in the vagaries of our own lived experiences. Their works are necessarily *evocational* rather than *informational*; they seek to illuminate rather than to problem-solve. They invite our active participation, reflection and hence self-transformation. One such memorable and provocative piece of work is that of the poet John Keats who draws us into the mystery of a Grecian urn which he happened upon in one of his visits to a museum in London. *Ode on a Grecian Urn* (Keats, 1884: 41) invites us to ponder on what is contained in the history of an ancient piece now standing quietly and unobtrusively in a corner in the British museum. The urn's decorative carvings depicts characters and plants that possibly betray the happenings of a bygone age and this makes Keats ponder on what tale lay hidden behind its physical presence.

> Thou still unravished bride of quietness
> Thou foster child of silence and slow time
> Sylvan historian, who canst thus express
> A flowery tale more sweetly than our rhyme
> What leaf-fringed legends haunts about thy shape
> Of deities or mortals, or of both
> In Tempe or the dales of Arcady?
> What men or gods are these? What maiden loath?
> What mad pursuit? What struggle to escape?
> What pipes and timbrels? What wild ecstasy?

Keats here invites us into the unfathomable mystery that surrounds the Grecian urn by drawing our attention to the historical background, to its rich unaccounted and unaccountable *absence* that renders possible its eventual *presence* as a solitary showpiece in a faraway British museum. Reading Keats, we are left with a sense of incompleteness and of irreducible uncertainty. We cannot ever really know. Nevertheless, by dwelling in the unanswered mystery that is the Grecian urn, we are led to gradually appreciate more and more the power and fecundity of vagueness and ambiguity in evoking our inner sensibilities. There is a certain *inexhaustible* richness and complexity about whatever is met in human experiences. Vagueness, it seems, can be a virtue in that it elicits our awareness of the necessity for complex thinking. The same impulse towards the complex can be discerned in our encounters with the *imperfect*.

THE SUBLIMINAL APPEAL OF THE IMPERFECT: RUSKIN'S 'NOBLE PICTURESQUE'

> Imperatively requiring dexterity of touch, they gradually forgot to look for tenderness of feeling; imperatively requiring accuracy of knowledge, they gradually forgot to ask for originality of thought. … they were left to felicitate themselves on their small science and their neat fingering. (Ruskin, 1903–1912, Vol. XI: 15)

The love for the richness and the oftentimes inexplicable attractiveness of the old, the gnarled and the decayed – an appreciation of the detailed variety of life experiences, in contrast to the neat and well-ordered symmetries we ordinarily encounter – led the art critic and social reformer John Ruskin to coin a phrase the 'noble picturesque' to describe the sentiment that the former seems to inexplicably evoke in many of us. He reflects on this experience on one of his many visits to Calais:

> I cannot find words to express the intense pleasure I have always in first finding myself, after some prolonged stay in England, at the foot of the old tower of Calais church. The large neglect, the noble unsightliness of it; the record of its years written so visibly, yet without sign of weakness or decay; its stern wasteness and gloom, eaten away by the Channel winds; and overgrown with the bitter sea grass; its slates and tiles all shaken and rent, and yet not falling; its desert of brickwork, full of bolts, and holes, and ugly fissures, and yet strong like a bare brown rock; its carelessness of what anyone thinks or feels about it, putting forth no claim, having no beauty or desirableness, pride, nor grace; yet neither asking for pity. … (Ruskin, 1903–1912, Vol. VI: 11)

Ruskin contrasts this with the 'spirit of trimness' found in nineteenth century England; the predictable 'spikiness and spruceness' exemplified by their neat and orderly fencings and gates, their well-cared lawns, the smooth paving stones and hard, even, rutless roads. Here in this orderly and ordered Victorian world, there was little 'confession of weakness' that made it all the more unattractive. For Ruskin, somehow, the gnarled, the weathered, and the decayed harbour a strange attractiveness that awakens in us an appreciation for the nobility of impoverishment and the 'unconscious suffering' endured by 'unpretending strength of heart' (Ruskin, 1903–1912, Vol. VI: 14). It is such an aesthetic appreciation for the noble picturesque that helps us to recognize that the complexity in social life and management is not reducible to the trimness and predictability of an established order. Rather, social life is ennobled by the chaos and inherent messiness found in everyday situations and the way they often surprisingly generate multiple possibilities and outcomes of their own accord.

The obsessive desire to always intervene, to make things tidier and to restore what is considered imperfect, results in a lack of substance; a simplifying uniformity that is relatable to Morin's 'paradigm of simplification'. In modern designed architecture, for instance, buildings lose their distinction for want of contrast. Each architect and worker is compelled by the imposed common purpose to achieve a unitary outcome. The character of the buildings become ever more anodyne. In gothic architecture, however, the contrasts are changed, almost at whim, lest they become too uniform; squares are met with diamonds, verticals with curves and courses with alternates. The whole is a local assemblage, making full use of available materials in their most unadorned form and free from the over-weaning strictures of an imposed end-point or purpose. This *gothic sensibility* intimately associated with Ruskin's notion of the 'noble picturesque' encapsulates an attitude, not of passivity, but of enduring life as naturally as is possible, to immerse oneself in the open-ended intricacies of nature without hankering after completion, essences and certainty. The gothic takes as a pattern nature itself; its tempering and massing of light and shade, of colours, of rock and foliage, of sky and earth, in ways that cannot be reduced to constituent elements or repeating symmetries. Ruskin's veneration of the great gothic cathedrals of Europe was born of this recognition. *The buildings hit you not because of their perfection and completeness, but their animated endurance. They were built over generations in a spirit of belonging, penitence, humour and emergence; becoming collective expressions of lived tradition.*

Ruskin's 'noble picturesque' and gothic sensibility in their elevation of the varied, the nuanced, and the imperfect, mirror the inherent frailties and the limitations of human comprehension and encapsulate *obliquely* the kind of complex thinking we have identified to be well appreciated in the arts and humanities. Against the spectacular, confident, well-ordered precision of Renaissance designs, the gothic sensibility, with its open-endedness, transparent honesty and frank and public confession of weakness, reverberates much more with the lived experiences and vulnerability of everyday lives, including especially those of organization and management practitioners. These are the very qualities that make for a deeper appreciation of what a 'paradigm of complexity' implies in researching and understanding organization and in the practice of management.

COMPLEXITY AND THE *OBLIQUE* APPROACH IN MANAGEMENT: DISCERNING THE HIDDEN PROPENSITY OF THINGS

> The history of strategy is, fundamentally, a record of the application and evolution of the indirect approach … The indirect approach is as fundamental to the realm of politics as it is to the realm of sex. (Basil Liddell-Hart, *Strategy:* 1967, pp. xix–xx)

An appreciation of the ubiquity of complexity leads to the cultivation of an oblique and nuanced approach to management; one that recognizes the limitations and frequently self-defeating consequences of directly attempting to confront and overcome problems when dealing with the world of human affairs. Paradoxically, *the more a specific management situation is directly and deliberately apprehended, the more likely it is that such actions generate adverse ripple effects that eventually work to undermine their own initial successes.* This is because direct interventionist action is by nature *intrusive*: it forces itself into the natural course of things and 'inevitably … tears at the tissue of things and upset their coherence' (Jullien, 2004: 54, in Chia and Holt, 2009: 191) invariably provoking elements of resistance that work to undermine it. Thus, the more obsessively bottom-line and success-focused an organization is, the more it tends to gloss over the very crucial, but mundane factors that make such success possible in the first place. Or as the eminent economist John Kay (2010: 8) rightly observes, in his latest book *Obliquity: Why Our Goals are best Achieved Indirectly*, 'Happiness is not achieved through the pursuit of happiness. The most profitable businesses are not the most profit-oriented. The wealthiest people are not the most assertive in the pursuit of wealth. The greatest paintings are not the most accurate representations of their subjects'. This counterintuitive thinking is very much in keeping with a deep appreciation of the real significance of complexity in human affairs.

A corollary of this profound insight is that action that is generally deemed peripheral to explicitly-stated ends may surprisingly prove more efficacious in bringing about the desired outcome sought. Indirect, oblique action is often more *silently efficacious*. Action that is deemed *oblique* in relation to specified ends can often produce more dramatic and lasting effects than direct, focused action (Chia and Holt, 2009: x). Seemingly insignificant small gestures, that often go unnoticed, may produce transformational effects that reach far beyond their scene of initiation. It appears that there may be more wisdom in approaching managerial situations more modestly and elliptically allowing priorities to emerge spontaneously through local ingenuity and adaptive actions taken *in situ* than in directly addressing and confronting the deficiencies identified. Such an unspectacular approach often proves more sustainable than dramatic interventions. Indeed, there is much evidence to suggest that in the history of social progress and evolution, favourable outcomes are often not the deliberate design and machinations of any one individual or institution but the collective unintended outcome of a multitude of individuals each merely seeking to respond constructively to the predicaments they find themselves in. In other words:

> in seeking to explain individual, corporate and societal accomplishments there is no need to recur to deliberate intention, conscious choice and purposeful intervention. Collective success need not be attributable to the pre-existence of deliberate, planned and coordinated action. (Chia and Holt, 2009: x)

This idea that outstanding accomplishments are not necessarily the product of deliberate intention and action has been noted by the Scottish Enlightenment thinker Adam Ferguson in his study of the progress of civil society:

> Mankind … in striving to remove inconveniences, or to gain apparent and contiguous advantages, arrive at ends which even their imagination could not anticipate … Every step and every movement of the multitude, even in what are termed enlightenment ages, are made with equal blindness to the future, and nations stumble upon establishments, which are *indeed the result of human action, but not the execution of any human design*. (Ferguson, 1767/1966: 122, in Chia and Holt, 2009: 31, emphasis added)

Such un-designed spontaneous emergence identified by Ferguson has been taken up and advocated by the Austrian economist Frederich Hayek (1948) as the basis for understanding complex economic and social phenomena and this has also been shown, to have affinities with the new science of complexity. It is an approach that provides us with an alternative basis for understanding and managing complexity. Contrary to the notion of deliberate, decisive and boldly executed action, this notion of 'silent' spontaneous emergence carries with it a number of implications with regards to how social phenomena and especially managerial situations are to be viewed, investigated, apprehended, and dealt with.

There are three key orientations that can be associated with this more oblique approach to the management of complexity. First, the widespread notion that focused, decisive, and overt action is most efficient in engaging with the world of affairs, must be tempered by a more subtle appreciation of how it is that oftentimes such direct interventions create unintended negative consequences because of the internal resistances they precipitate. Conversely, desired outcomes are often the unintended effect of mundane local coping actions that appear impressive only in *retrospect*. Hence, looking for and attributing successful achievements to the heroic intentions and rational actions of individuals or agents may prove counterproductive in our attempt to understand how it is in practice, positive results have actually been achieved. Second, in seeking a compelling explanation for such positive outcomes, we must resist the instinctive tendency to look towards externally-initiated spectacular or dramatic interventions as decisive 'turning points' in accounting for success. Rather the cause for transformation may be latent and *immanent*; there is an internal momentum or 'propensity of things' (Jullien, 1999) that drive events and situations and this must be recognized and capitalized upon in the art of management. Finally, both researchers and practitioners must re-tune their sensitivities towards the *hidden*, the *inconspicuous* and the *peripheral* to fully appreciate the *labyrinthine* nature of everyday happenings.

Seeking the hidden, the inconspicuous and the peripheral

Complex thinking with its sense of the gothic and the 'noble picturesque' implies looking at the overlooked; sifting through the fragments, cracks, variations and inconsistencies beneath the superficial gloss and appreciating how these surface appearances of coherence and unity belie a deeper messier and at times logically incoherent managerial reality. It demands a certain resistance to the seductions of the dramatic, the spectacular and the eye-catching and the cultivation of an aesthetic sensitivity for the potentiality of the unshapely, the unsightly, the unwieldy and the unattractive. It requires a 're-education of attention' (Chia, 2004); one that is particularly attentive to the hidden, the inconspicuous, and the marginalized 'outliers' (Gladwell, 2008) that reside at the periphery of attention. For, it is only through painstakingly attending to the detailed and mundane matters of daily life that we begin to truly appreciate what goes on in the real world of organization and management. Practising managers are so immersed in their everyday worlds that, for the most part, there is virtually no distance between thought and action. Their knowledge is, as the French sociologist Michel de Certeau puts it well, 'as blind as that of lovers in each other's arms' (de Certeau, 1984: 93) and the logic of practice 'is not that of the logician' (Bourdieu, 1990: 86). Positive outcomes may ensue even though actors themselves may be unaware of how their actions and preferences belie an acquired consistency not of their own making. In pointing the way and creating a space for the legitimacy of non-deliberate action, de Certeau and Bourdieu, like Hayek and the Scottish Enlightenment thinkers, have made it possible for us to think more complexly about how successful management like social accomplishments such as language, money and social institutions may be achieved without anyone actually having a clear and justifiable plan of action.

In thinking complexly, in accounting for any form of managerial success we must be mindful of unconscious, oblique and obscure causes that may affect the balance and potentiality of situations such that desirable outcomes ensue without anyone being particularly aware of how they have come to pass. In his most recent book entitled *Outliers: The Story of Success* the popular writer Malcolm Gladwell shows that oftentimes a cause as inconspicuous as birthdates and cut-off points for recruitment can have a dramatic overall effect on the fortunes of a young aspiring Canadian hockey player. Citing the sociologist Robert Merton's analysis of 'The Matthew Effect' (Merton, 1968), in which there is a built-in tendency in social systems to give those who have even more and those who do not even less, Gladwell (2008: 30–33) shows how it is that a closer examination of the birthdates of those deemed successful in hockey revealed that they were largely born between January to March and this was surprisingly a major contributory factor to their success. Something as innocuous as birthdate can tip the scales for or against any individual youngster aspiring to be a professional hockey player. Citing research on this phenomenon of success amongst hockey players and other sports, Gladwell shows that, in any sporting season, because those nine and ten year olds born in the beginning of the year are invariably bigger than those born later in the year, they tend to get more coaching and practice than their counterparts and this makes them appear naturally better than those born later. As a result they get the best treatment and best breaks and are more likely to become professionals in their sport. Success, it turns out, is not so much about innate individual abilities, but a result of cumulative advantages built into the system not through any one deliberately intending it to be so. The real reason for success may be more serendipitous and obscure than generally acknowledged.

How can this indirect and more complex approach to understanding the nature of success be brought into the realms of management and what implications do they have for the way management should be practiced?

The silent efficacy of oblique action

In a recent Harvard Business Review paper entitled ‘Strategy as Active Waiting’ Donald Sull argues that oftentimes golden opportunities have a tendency to ‘come from afar’ such that the moment of maturation, ‘the window of opportunity’, is often rare and fleeting. As such managers must pay attention to hidden anomalies and try to identify and understand possible subtle shifts that create new opportunities for exploitation. ‘The variables that influence the magnitude of an opportunity shift constantly. One window might open a crack, while another widens abruptly and a third threatens to slam shut’ (Sull, 2005: 123). Central to understanding the inner propensity of things is the idea that opportunity or the opportune moment is not something that needs to be grabbed, but subtly discerned a long way before it becomes an actuality. Hence, the skill of a manager is in ‘spotting a propensity’ in such a way that s/he sees at the earliest stage a tendency that emanates from this and thus does not need to needlessly strive to achieve the effect. Rather like patiently waiting for a fruit to ripen before it is plucked, one lets the course of things to work its way towards one’s own advantage. This is something that the ancient Chinese thinkers well understood.

> As Mencius points out, one must neither pull on plants to hasten their growth (an image of direct action), nor must one fail to hoe the earth around them so as to encourage their growth (by creating favourable conditions for it) … You must *allow it to grow* … *allowing* things to happen constitutes active involvement. (Jullien, 2004: 90–91, emphasis original)

Sull’s (2005) use of ‘active’ in describing waiting alludes to a ‘non-doing’; it is an oblique or silent form of doing. By eschewing grand visions and spectacular strategies, and focusing on long-term trends and priorities, what Sull urges is going with the propensity of things. As Jullien aptly states, ‘one can “act without acting” just as one can “taste a nontaste”. Acting, like tasting, can then extend of its own accord, excluding nothing; it is “inexhaustible”’ (Jullien, 2004: 89). This unspectacular and non-confrontational approach to achieving longer-term tangible outcomes resonates with another recent contribution to strategic management.

In *Blue Ocean Strategy*, Kim and Mauborgne (2005) argue that rather than follow the logic of confronting competitors and attempting to out-perform them thereby creating a ‘bloody’ red ocean of competition, corporations ought to seek out new *blue oceans* of as-yet-untapped opportunities thereby making the competition irrelevant.

This *indirect* and non-confrontational approach contains an implicit recognition that efficacy can often be achieved by *avoiding* and *circumventing* the opposition rather than directly clashing with the latter. Although Kim and Mauborgne's propositions are couched in the more familiar strategy language of deliberate and calculated intervention, in this instance into new market spaces, what belies their thinking is an implicit awareness that the potentiality inherent in a situation can be exploited to one's advantage without adverse costs in terms of resources. Instead of setting out a goal for our actions, we could try to discern the underlying factors whose inner configuration is favourable to the task at hand and to then allow ourselves to be carried along by the momentum and propensity of things. Jullien (2004: 17) writes:

> Two notions thus lie at the heart of ancient Chinese strategy, forming a pair: on the one hand, the notion of a *situation or configuration* (*xing*) as it develops and takes shape before our eyes (as a relation of forces); on the other hand, and counterbalancing this, the notion of *potential* (*shi*), which is implied by that situation and can be made to play in one's favour.

Jullien points out that these two notions, embedded in ancient Chinese thinking, call into question the 'humanist concept of efficacy' which presupposes efficacy to result from direct, spectacular human interventions. According to this more oblique way of engaging with the world of affairs, all one needs to do is to *allow* the momentum and potential of the situation to unfold itself almost inexorably towards its natural end and to position oneself to benefit from it. Thus with very little effort one can seemingly produce 'great effects'. What is crucial in this approach is not so much grand visions or bold, spectacular plans but subtle sensitive reading and evaluation of the unfolding situation. The art of success, given the multiplicity and complexity of the social world, then, it seems is the 'silent' art of *discernment*.

Both Sull's (2005) notion of 'strategy as active waiting' and Kim and Mauborgne's (2005) *blue ocean* approach point towards a new-found preference for the subtle efficacy of obliqueness of engagement. Both eschew the instrumental, action-oriented, frontal and heroic confrontational approach that is not just second nature to much of Western military, social and political life but very much in evidence in the American-inspired academic literature and practice of management. This shift of attention towards the efficacy of the oblique is also being played out in the surprising global turn of events in recent years where a shift in the balance of economic power from West to East is gradually taking place. What the celebrated Scottish Harvard-based historian Niall Ferguson calls 'Chimerica' – where China saved to fuel America's unsustainable spending extravagance over the past decade – has given rise to the most bizarre situation where China has effectively 'become banker to the United States of America' (Ferguson, 2008: 334). Whilst America was seduced by its own rhetoric of national and corporate success during the boom years prior to the financial crisis, it was cheap Chinese money which kept the American economy going. To keep the good times rolling, during the boom years, America imported cheap Chinese goods, outsourced manufacturing to China and sold 'billions of dollars of bonds to the People's Bank of China' (Ferguson, 2008: 334–335) in order to enjoy low interest rates. Chimerica was 'the underlying cause of the surge in bank lending, bond issuance and new derivatives … It was the underlying reason why private equity partnerships were able to borrow money left, right and centre to finance leveraged buyouts'. And, Chimerica, or the Asian 'savings glut' (Bernanke, 2005) was the 'underlying reason why the US mortgage market was so awash with cash in 2006 that you could get a 100 per cent mortgage with no income, no job, no assets' (Ferguson, 2008: 336).

This inextricably entangled nature of the globalized world suggests to us that obliqueness of influence and the ripple effects of peripheral actions and non-local causality have become important considerations in our evaluation of local circumstances and their wider ramifications. Learning to think complexly is learning to appreciate and discern the seemingly inconspicuous, the peripheral and the as-yet undisclosed. Managing complexity entails the art of seeking out the obscured, the hidden and the implicit and dealing with them before they manifest themselves explicitly. It encourages us to recognize *obliquity* as a legitimate and oftentimes more efficacious strategy in dealing with human affairs.

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Methodological Implications and Tools

12

Applications of Kauffman's Coevolutionary *NKCS* Model to Management and Organization Studies

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INTRODUCTION

A number of studies have used tuneable, abstract models of organism evolution like Kauffman's (1993) *NK* model to capture and explore aspects of organizations and their adaptation in the business environment (e.g. Levinthal, 1997; Rivkin, 2000; Lenox et al., 2007; Rivkin and Siggelkow, 2003, 2007). However, these studies have not typically considered the fact that organizations exist within an ecosystem of other organizations, and further that a large organization may be seen as an ecosystem of semi-autonomous departments itself. Whereas the *NK* model has been adopted and extended by many researchers, applications of the coevolutionary *NKCS* model are sparse. A number of researchers have used the *NKCS* model as a theoretical lens but few have built an *NKCS* implementation and experimented with it in the social science domain.

In the *NK* model, *N* refers to the number of genes in a genotype and *K* the number of links between those genes (internal epistasis). Agents are thrown on to a fitness landscape (Wright, 1932) at random and then seek to improve their fitness by engaging in an adaptive walk. A key feature of the *NK* landscape is that it is fixed: agents walk on it without deforming. Further, these agents are typically oblivious of other agents, although Lazer and Friedman (2007) introduce communication networks within the *NK* model, allowing agents to share knowledge about their fitness level. By contrast, the *NKCS* model allows for coupled landscapes (through external epistasis, *C*) and multiple species, *S*. A movement by one species on its *NK* landscape deforms the landscapes of those species with which it is coupled and thus the *NKCS* model represents the dynamics of a coevolutionary system.

The aim of this chapter is to explore the *NKCS* model and to understand its implications and possibilities for informing management and organizational research. To this end we first explore the idea of coevolution, then introduce the details of the *NKCS* model and its implementation in an agent-based modeling environment – Sendero (Padget et al., 2009). Having shown the mechanics of the *NKCS* model we then review the applications of the *NKCS* model in the management and organizational studies literature. To demonstrate how the *NKCS* model can be extended and applied to the management discipline we show how the *NKCS* can be used to explain the dynamics of competition in the microcomputer industry. The chapter concludes with thoughts about future directions for the *NKCS* model and coevolutionary research in management studies.

EVOLUTION AND COEVOLUTION

The study of organizational evolution in the management literature builds on work in organizational ecology (Carroll, 1984; Hannan and Freeman, 1989). Nelson and Winter (1982) view organizations as comprising routines and sets of activities. McKelvey (1982) labels these routines 'comps', a shorthand for the competencies that represent an organization's capabilities. Routines can also be thought of as rules and standard operating procedures, which may or may not be observable. Regardless of how they are defined these routines (or comps) are assumed to be subject to the evolutionary process.

Aldrich and Ruef (2006) see the evolutionary process as consisting of variation, selection, and retention within a background of a struggle for scarce resources. Aldrich and Ruef (ibid.) aim to show how evolutionary concepts can be applied to organizations and thus their examples are couched in organization language. Variation is any change in an organization's routines, competencies, or form and can be intentional (alternatives and solutions are actively sought by actors in an organization) or blind (independent of conscious planning). Others, e.g. Campbell (1965), would argue that variation is always blind in the sense that the evolutionary outcome cannot be known at the time of the variation event and therefore intentional variation is at best an educated guess. Regardless, not all the variations will survive; the selection force results in the elimination of some of the variations. Selection pressure on routines and competencies can be either external (e.g. market forces and competitive pressures on an organization) or internal (e.g. a pressure toward stability). Through retention the selected variations are preserved and duplicated (e.g. standardization and institutionalization of a new role).

Although coevolution arises in the nineteenth century from Darwin's *The Origin of Species* the first half of the twentieth century was a barren time for coevolutionary research and it was not until the 1950s that work in evolutionary ecology and population genetics set the scene for work by Ehrlich and Raven (1964) on plants and insects and by Janzen (1966) on ants and acacias (Thompson, 1999b). Where evolution considers a single population, coevolution is concerned with how populations interact and coevolve. Coevolving populations are each subject to the evolutionary dynamics of variation, selection, and retention. For two populations to coevolve requires each population to apply a reciprocal selection force on the other. As one species responds to a selection pressure from a second species it evolves and in turn applies a selection process to its coevolving partner. Thus, a species of seashell that is being predated by a crab may, over time, evolve a thicker shell. This development of the seashell in turn applies a selection pressure on the crab, which may in response evolve yet more powerful claws. In such a case, the selection pressure is reciprocal and the species can be said to be coevolving. Janzen (1980) defines coevolution as follows:

> 'Coevolution' may be usefully defined as an evolutionary change in a trait of the individuals in one population in response to a trait of the individuals

> of a second population, followed by an evolutionary response by the second population to the change in the first. (p. 611)

Bateson (1979) similarly sees coevolution as reciprocal where changes in one species, species A, 'set the stage for the natural selection of changes in a species B' (p. 227) such that later changes in species B in turn set the stage for the selection of further changes in species A. In talking about how the genomes of different species become intermeshed Thompson (1999a) also emphasizes the reciprocal nature of coevolution and recognizes that this intermeshing can be competitive or mutually beneficial:

> The organizing framework for attacking the problem is the theory of coevolution, the process by which species undergo reciprocal evolutionary change through natural selection. Not all interactions are highly coevolved, but the potential for coevolution to drive rapid and far-reaching change is always there. Unlike adaptation to the physical environment, adaptation to another species can produce reciprocal evolutionary responses that either thwart these adaptive changes or, in mutualistic interactions, magnify their effects. (p. 2116)

Although these examples come from biology, demonstrating coevolution is not straightforward in the natural world given long generation times and the difficulty of establishing that species are truly coevolving rather than each merely adapting to their environment (or coevolving via a third but unobserved species). In an organizational setting change can be intentional and action reflexive making coevolution a particularly useful and tenable concept. Aldrich and Ruef (2006) look at the relationship between coevolving populations in terms of symbiosis and mutualism. Symbiosis refers to mutual dependence of dissimilar units, each in different niches but each benefiting from the presence of the other (e.g. venture capitalists and high technology companies). Mutualism is concerned with over-lapping niches with a spectrum of cooperation (species benefit from the presence of other species) and competition (growth in one population restricts growth in another population). Metcalfe (1998) identifies three configurations of coevolution: competition, exploitation, and mutualism. In competition one configuration seeks to hinder the fitness of other configurations (full competition). In exploitation one configuration stimulates the fitness of another but is in turn inhibited by that other (predatory competition). In mutualism each configuration stimulates the individual and collective fitness (full mutualism).

Coevolutionary relationships of symbiosis and the various forms of mutualism would be expected to occur between and within organizations. Full mutualism may be an appropriate outcome for inter-organizational processes established between cooperating organizations, such as in a supply network, although, depending on the balance of power between customers and suppliers, there may well be exploitation. In other configurations full competition would be appropriate, as would likely be the case for organizations targeting the same market with undifferentiated product offerings. Similarly, within organizations different configurations of mutualism would be expected to be found although this might not necessarily be healthy, for example where an IT strategy seeks to improve its own fitness at the expense of the host organization as a result of misplaced viability seeking (Beer, 1979). In summary, coevolutionary theory would appear to provide management researchers with a rich and insightful way of thinking about inter- and intra-organizational relationships.

THE *NKCS* MODEL

Kauffman and Johnsen (1992) introduced the *NKCS* model to allow the systematic study of various aspects of natural coevolution between interacting species (although, since the model is abstract it can be applied to the study of any collection of interacting agents that are adapting to the current state of other agents). In the *NK* model a given agent is represented by a set of *N* genes, each with *A* possible states. In the *NKCS* model a population is assumed to be converged to all individuals having the same value for each constituent gene, i.e. there is a single agent that represents the fitness of a species and therefore an ecosystem with five species would be represented by a coevolutionary set containing five agents.

The fitness of the individual agent depends upon the contribution made by each gene, each of which depends upon *K* other genes (randomly chosen) within the agent (epistasis). Increasing *K*, with respect to *N*, increases the epistatic linkage, increasing the ruggedness of the fitness landscape of an agent by increasing the number of fitness peaks, increasing the steepness of the sides of the peaks such that the space becomes increasingly complex. Each individual gene is also said to depend upon *C* genes (randomly chosen) in the other agents with which it interacts. Hence, the adaptive moves made by one agent may alter the fitness landscapes of its (*S*) partners; altering *C*, with respect to *N*, changes the extent to which adaptive moves by each individual deforms the landscapes of its partnering agents. As *C* increases, mean evolutionary fitness drops and the time taken to reach an equilibrium point increases, where the fitness level of the equilibrium decreases.

The model assumes all inter-agent (*C*) and intra-agent (*K*) interactions are so complex that it is only appropriate to assign random values (uniform random distribution) to their effects on fitness. Therefore for each of the possible $K+C$ interactions, for each given replicator and assuming that the number of states a gene can take is $A = 2$, a table of $2^{(K+1+C\text{x}S)}$ fitness contributions is created, with all entries in the range [0.0, 1.0], such that there is one fitness for each possible combination. The fitness contribution of each agent within an experiment is found from its individual table. These contributions are then summed and normalized by *N* to give the actual fitness of the individual.

Kauffman and Johnsen (1992) used random hill-climbing to evolve each agent in turn, i.e. each agent uses the current context of the others to determine whether a random alteration to its configuration represents progress. That is, from a given configuration, an agent randomly alters one gene's state and calculates the resulting fitness. If the new fitness is greater than the agent's current fitness, in the current environment, the agent adopts the new configuration. This is repeated for all agents over a number of generations. They show how both intergenome (*C*) and intragenome (*K*) epistasis affects a coevolving system, particularly in the attainment of Nash equilibria: 'a combination of actions by a set of agents such that, for each agent, granted that the other agents do not alter their own actions, its action is optimal' (Kauffman, 1993: 245).

As an example, in Figure 12.1 frog and fly species are each characterized by an *NKCS* landscape. Each gene in the frog depends on $K + C$ inputs; for gene *n3* (this could be the sticky tongue of the frog) in Figure 12.1 fitness depends on $K = 3$ other traits in the frog and $C = 2$ traits in the fly (such as slippery feet). A movement by the frog population on its landscape deforms the fly's landscape, and vice versa.

Emergent regimes in the NKCS *model*

Kauffman (1995b) identifies two extreme behaviors relating to coupled landscapes. The first is the 'Red Queen Effect' (RQE), coined by Lee Van Valen (1973) from the Red Queen saying to Alice 'it takes all the running you can do, to keep in the same place'. In this regime the species keep changing their genotypes in a never-ending race to improve their fitness level. The population never settles down to an unchanging mix of genotypes as species chase peaks that recede into the distance. The second scenario is of coevolving species that reach an evolutionary stable strategy (ESS) and then stop changing genotypes.

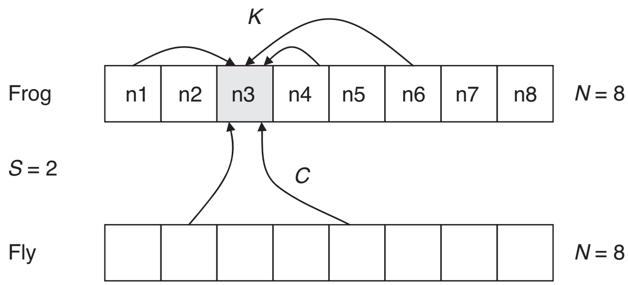

Figure 12.1 Coupled landscapes in the *NKCS* model (adapted from Figure 8.16 from "Investigations" by Kauffman (2000), p. 200). By permission of Oxford University Press, Inc.

Species that have attained an ESS have succeeded in climbing to a peak and remaining on it – coevolution ceases and an ordered regime emerges, although it is likely that this peak is not a particularly high one. As in the prisoner's dilemma, a species has no incentive to change as long as its partnering species do not change. Kauffman (1995a) sees Red Queen behavior as chaotic with species climbing and plunging while the ESS is an ordered regime that is overly rigid and unable to move away from suboptimal local peaks (p. 221). Kauffman (ibid.) demonstrated that 'the highest average fitness in coevolving systems appeared to arise just at the phase transition between Red Queen chaos and ESS order' (pp. 257–258). This phase transition is a place favored by coevolution, the so-called 'edge of chaos' (Kauffman, 1995a):

> An ecosystem deep in the ordered regime of an evolutionary stable strategy will be too rigid, too frozen into place, to coevolve away from low local peaks. Under the chaos of the Red Queen effect, on the other hand, species climb and plummet on heaving fitness landscapes, never staying at a peak. But between these two extremes of low fitness, in the transition between chaos and order at the 'edge of chaos', peaks are high but can be attained. Here, fitness can be optimized.

Brown and Eisenhardt (1998) say that organizations that achieve the edge of chaos will compete more effectively than those that don't; at the edge of chaos 'organizations never quite settle into a stable equilibrium but never quite fall apart, either' (p. 12). This view is supported by Anderson (1999) who claims 'Systems that are driven to (but not past) the edge of chaos out-compete systems that do not' (pp. 223–224). Lewin and Volberda (1999) summarize the importance of achieving the edge of chaos for organizations:

> At this 'edge of chaos', an organization is assumed to optimize the benefits of stability, while retaining capacity to change by combining and recombining both path dependence and path creation processes. Such an organization creates sufficient structure to maintain basic order but minimizes structural interdependencies. It evolves internal processes that unleash emergent processes such as improvisation, self-organizing, emergent strategies and strange attractors (e.g. product champions). (p. 530)

In the context of organizations it is better, perhaps, to think of a complex region rather than an 'edge'. This region lies between stasis and chaos and is defined by two critical values. If an organization falls below the first critical value because it exhibits minimal response to addressing the adaptive tensions it faces then order will prevail. If the organization over-responds to its adaptive tensions, for example by initiating many change programmes too quickly, then it may exceed the second critical value and chaos will ensue. Kauffman finds that the ecosystem settles to an ESS if the internal density of connections, *K*, within species are high (there are a lot of low peaks to be trapped on) and the coupling between the species is low (landscapes do not deform much as a species makes an adaptive move). The ESS ordered regime also emerges when the number of species is low (e.g. moves by one process do not deform the landscape of many other processes). An ordered regime, therefore, emerges when *K* is high and *C* or *S* is low. A chaotic regime emerges when *K* is low and *C* or *S* is high. Somewhere in between is the complex region. In the next section we introduce an implementation of the *NKCS* model, Sendero, and demonstrate these three regions.

AN AGENT-BASED MODELLING IMPLEMENTATION OF THE *NKCS*: SENDERO

Sendero implementation in Repast

The following description of the software implementation of the *NKCS* model is taken from Padget et al. (2009). The approach taken to constructing the *NKCS* model was to first build a basic version of the *NK* model and to dock it to Kauffman's (1993) reported results. Having done this, Padget et al. then extended the *NK* model to address the more complex *NKCS* landscape, using the same techniques wherever possible.

The model was implemented using the RepastJ (North et al., 2006) agent-based simulation toolkit. To generate random fitness values and landscape locations the Colt Mersenne Twister random number generator supplied with RepastJ was used. In the *NKCS* model each coevolutionary set was implemented in the Repast framework as an agent. These sets contain a number of species, each with its own distinct landscape. At each generation of the simulation, the species take turns to move on their own landscapes, which are perturbed by the movements of the other species in the set. To describe the coevolutionary process, data is collected at the level of the individual species.

From the implementation perspective the calculation of fitness is almost identical between *NK* and *NKCS* and is performed by the same method. In both cases, for each characteristic, a string is built representing the state in base *A* (*A* is typically dichotomous and therefore set to 2 but it can take any value equal to or greater than 2), of the characteristic itself, and the *K* characteristics that influence it. To extend this to *NKCS* Padget et al. add to the string the states of the *C* characteristics of each of the *S* other species to which the species under examination is linked. This string is then assigned a random fitness value and stored.

Having decided on the specification of the models, a significant challenge was the representation of the fitness landscape itself. In both the *NK* and *NKCS* models the landscape possesses a finite number of states (albeit an extremely large number in the case of *NKCS*). The fitness of agents at given locations is randomly assigned in response to the characteristics of the location (and, for *NKCS*, the location of other species in the set). At the same time, an agent arriving at a location that it (or another agent) has previously visited must be awarded the same fitness value as reported earlier. Sendero computes and stores location fitness values only when they are first visited by an agent (or checked as a possible candidate to be moved to). In this way the need to store the entire landscape is avoided (much of which may never be visited in the course of the simulation). However, there is no alternative to storing the fitness values for all of the locations that have been visited or checked. This space requirement represents the major constraint on simulation size in the Sendero implementation. In runs where the required landscape is large (or numerous landscapes are used, in *NKCS*), or large numbers of organizations walk extensively on the landscape, gigabytes of memory can be consumed.

Results of the base NKCS *model*

We saw above that an ordered regime emerges when K is high and C or S is low and a chaotic regime results when K is low and C or S is high. More specifically, Kauffman (1993: 253) finds that when $K < S \times C$ the properties of an ESS are observed; when $K > S \times C$ the system is characterized by the RQE, and when $K = S \times C$ (the region of intermediate complexity) fitness is best. We illustrate this using a range of C and K values for a pair of species in Table 12.1. On the diagonal $K = S \times C$ and it can be seen that fitness is highest for a given value of C. In Figure 12.2 the data in Table 12.1 is presented in graphical form as the percentage of coevolutionary sets still walking.

With the ESS the coevolutionary sets quickly stop walking as Nash equilibria are attained readily, most strongly for the case where $C = 1$ and $K = 16$ (Figure 12.2). Chaotic behavior is most extreme when $C = 8$ and $K = 2$ – by 1500 generations all 100 coevolving pairs are still walking as each species continues to disturb its partner and Nash equilibria cannot be found. For each value of C, fitness is best at the edge of chaos (the complex region) where $K = S \times C$.

APPLICATIONS OF THE *NKCS* MODEL

General applications

Whilst the *NK* model has been used quite extensively in areas such as function optimization (e.g. Altenberg, 1994; Smith and Smith, 1999; Correia and Fonseca, 2007) and evolutionary biology (e.g. Macken and Perelson, 1989; Ohta, 1998; Welch and Waxman, 2005), the *NKCS* model is less well exploited. As noted, Kauffman and Johnsen (1992) used it to explore aspects of ecosystem evolution. Bäk et al. (1994) continued this line of research, suggesting that when the coevolving species exist on maximally rugged landscapes, i.e. when $K = N\text{-}1$, no state of 'poised criticality' can be reached, only an equilibrium or chaos. Such considerations continue (e.g. Suzuki and Arita, 2005). Kauffman (1995a) later applied a spatially distributed version of the model to consider the effects of central control in government, and receiver-based communication protocols for pilot coordination by the US Air Force. Bull has used the framework to explore function optimization where the (large) global problem space is divided into (smaller) codependent subspaces, each being searched individually (e.g. Bull, 1997). He has also used it to consider the evolution of symbiogenesis (e.g. Bull and Fogarty, 1996) and multicellularity (e.g. Bull, 1999).

NKCS *APPLICATIONS IN MANAGEMENT AND ORGANIZATIONAL STUDIES*

Ahouse et al. (1992) argued that *NKCS* models need not be limited to coevolving species in biology and that the models could be applied 'in such diverse fields as economics, political science, organizational theory, and social psychology' (p. 349).

Table 12.1 For N = 24 and varying values of C and K, fitness is best in the complex region (the 'edge of chaos', EoC) where K = S × C (note: fitness is the average of 100 coevolving pairs after 1500 generations)

K	*C = 1*		*C = 4*		*C = 8*	
	S × C = 2		*S × C = 8*		*S × C = 16*	
2	**0.7160**	EoC	0.6110	RQE	0.5638	RQE
8	0.6900	ESS	**0.6748**	EoC	0.6049	RQE
16	0.6551	ESS	0.6507	ESS	**0.6379**	EoC

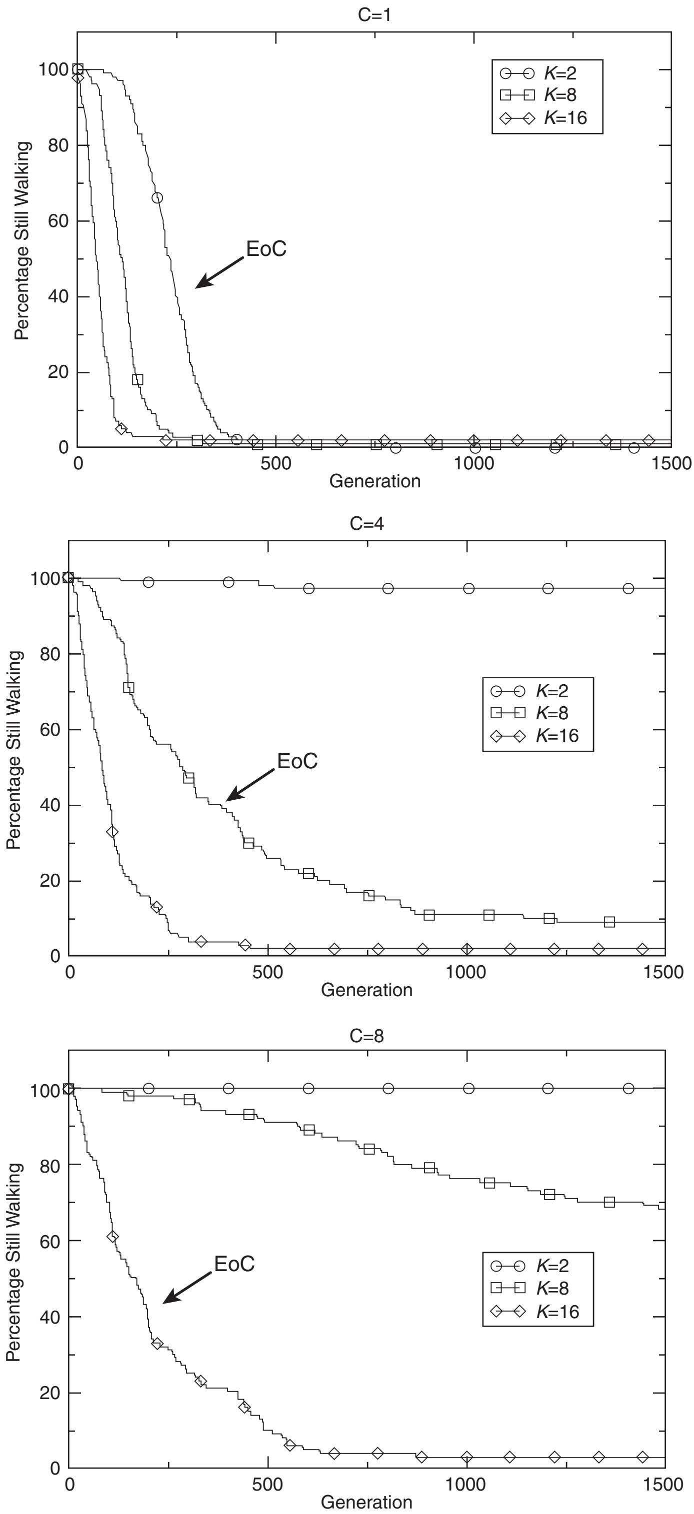

Figure 12.2 Percentage of 100 coevolving pairs still walking after 1500 generations for N = 24, C = 1, 4, 8 (note: EoC = 'edge of chaos')

Marion (1999) and Monge and Contractor (2003) have provided useful descriptions of the *NKCS* model and insightful critiques of the model's applicability in management studies. However, in conducting a review of previous work in management studies our criteria for work to be included was that it went beyond simply describing the *NKCS* model and attempted to apply the model to some domain of relevance to management researchers. Many of the studies reported in Table 12.2 take the basic *NKCS* model and show how it could, in conceptual form, be applied to management research (e.g. Baum, 1999). Other studies extend the *NKCS* (e.g. Chang and Harrington, 2003), while others go further and test the *NKCS* (with or without extensions) using a computer simulation (e.g. Levitan et al., 2002). Studies that apply the *NKCS* to empirical data are rather shorter in supply. Marion reinterprets a case study of the microcomputer industry using the *NKCS* as a lens, while Su and Mylopoulos (2006) conduct a behavioral study with information system analysts. Only one study uses the *NKCS* in a qualitative way: Colovic and Cartier (2007) use it to analyze case study data of inter-firm networks in Japan.

Monge and Contractor (2003) note that Chang and Harrington's (2000) application of the *NKCS* model introduces changes that remedy some of the simplifying assumptions of the *NKCS* model. Monge and Contractor (ibid.) also point out some of the simplifying assumptions in the *NKCS* that make it limited when applied to social systems:

- The *K* links between *N* traits are a constant value, e.g. each trait is linked to exactly three others. More realistically, *K* can be allowed to vary around a mean value (three, for example). Yuan and McKelvey (2004) were the first to run the *NK* model with *K* varying around the mean. A similar argument is made for *C*. Both of these extensions are implemented in Sendero (Padget et al., 2009).
- The number of links, *X*, between species is the same for all *S* species and the species each links to are chosen at random. In social systems the number of links between species will vary and the species will not be chosen at random. This facility is implemented in Sendero as a directed graph. For example, a supply network can then be modelled as an ecosystem in which the buyer/supplier links are specified explicitly, with varying degrees of *C*-coupling.
- Fitness values in the *NKCS* model are assigned randomly. Monge and Contractor (ibid.) argue that in social systems we have at least an intuitive sense of which traits may contribute more to overall fitness as compared with other traits (p. 288).

Marion (1999) also critiques the applicability of the *NKCS* to social systems, arguing that Kauffman 'is a bit naïve on the subject of social systems' (p. 268) and innocent in assuming that social systems function only on a fitness landscape with effectiveness the only motivation. In social systems factors such as the desire to control, power, preference for growth, preference for the status quo, and the desire to avoid change suggest that many interrelated landscapes need to be considered. A peak on a landscape represents a complex mix of preferences and is only partly understood. Marion concludes 'it really doesn't matter what the peaks are composed of, for the dynamics described by Kauffman still apply. Different preference landscapes, like different species, interact with and distort one another' (p. 269). And, through coevolution preferences are balanced relative to one another in a unique blend of 'power and efficiency and prestige and effectiveness and security' (p. 269) such that fitness in a broader sense is maximized.

Thus, once a basic *NKCS* model has been constructed there is a quickly reached limit to the findings and insights that can be achieved. Extensions to the *NKCS* model allow researchers to add features that capture aspects of social systems and acknowledge that management are not blindly walking a fitness landscape – they can intervene through tuning the model parameters.

Table 12.2 Applications of the *NKCS* model in management and organizational studies

Author	*Application*	*Research method*	*Findings and implications*
Ahouse et al. (1992)	Two applications of the *NKCS* are proposed: coevolution of firm strategies and coevolution of belief systems. For belief systems, species represent individuals who have *N* beliefs where each belief is reinforced or contradicted by *K* other beliefs. Each individual's beliefs are also affected by *C* beliefs of other individuals (species). Fitness is a measure of cognitive consistency. The model is also applied to nations to show how public opinion coevolves (see also Monge and Contractor (2003) for further details).	Conceptual	Claims that the *NKCS* can be applied outside of biology and coevolving species. Provides short descriptions of how the *NKCS* might be applied to competitive strategy and belief systems.
Kauffman (1995a)	Technological coevolution: the economy as an ever-changing web of increasing complexity in which new technologies (e.g. cars) enter and drive others (e.g. saddlery) extinct while creating new niches that create opportunities for further technologies (e.g. traffic lights).	Conceptual	Coevolution as an explanation of complements and substitutes in economics.
Caminati (1999)	For a given technology, the complementarity of its components increases over time and changes in a technology in one sector can transform technology in another sector. The *NKCS* is used to explain how technologies coevolve over time.	Conceptual	In the early stages of innovation the regime tends to be chaotic as technologies compete for dominance. The regime stabilizes as a winner emerges and large investments are made in that technology. Caminati (1999) speculates that this coevolving system can tune *K* and *C* through self-organization to achieve the complex region.
Baum (1999)	Kauffman's (1993: 248–249) findings for coevolving pairs of species with various *C* and *K* values are used to identify strategies for managing whole-part coevolutionary competition in organizations such that critical values are maintained and the organization attains the intermediate complex region.	Conceptual	Organizational interventions are identified for four strategies: (1) how to raise an organization's *K* when *C* is high (e.g. engage in incremental reorganizing), (2) how to lower an organization's *K* when *C* is low, (3) how to balance an organization's *K* and *C*, and (4) how to lower *C* (e.g. by increasing internal differentiation).
McKelvey (1999)	Value chain competencies of computer notebook manufacturers. A manufacturer has *N* competencies that are internally constrained by *K* other competencies and externally constrained by *C* competencies of competitors.	Conceptual	Firms need to match their internal complexity to their environment and focus on a moderate number of competencies.

Table 12.2 (*Contd.*)

Author	*Application*	*Research method*	*Findings and implications*
Marion (1999)	Applies the *NKCS* to Anderson's (1995) review of the microcomputer industry. Early manufacturers were small with low *K* and as the market developed large *K* players emerged (e.g. IBM) and competition, *C*, evolved while *S* reduced. In the early stages the industry is chaotic – *S* is high, *K* low, and *C* inconsequential. As *K* increased and *S* reduced the industry moved toward a stable regime.	Conceptual with reinterpretation of an empirical case study	Microcomputer industry fitness is a function of two interrelated activities: interdependence among actors in the network and the agreement on standards (e.g. the 3.5 inch floppy drive). Perturbations in the form of major technological changes become less frequent and of less magnitude as the industry matures and focuses on incremental fitness increases (e.g. clock speed).
Chang and Harrington (2000; 2003); Harrington and Chang (2005)	Coevolution of stores in competing retail chains serving customers in multiple markets. The *N* traits of each store represent store practices. *K* represents reinforcing and contradicting relationships between the practices. *C* reflects the interactions between the *N* practices of the competing stores. Fitness is concerned with attracting customers who make purchases proportional to their ideal practices and those offered by the store. Stores evolve and coevolve as they try one-step mutations to get closer to the ideal store practices of their customers. A headquarters species can propose mutations based on stores in its chain or on observed behavior of competitor stores. In centralized form the stores have little discretion in accepting HQ proposals; in decentralized form stores can override HQ.	Theoretical development with computer simulation	In cases of low market heterogeneity the population of stores does best with centralization (more inter-store learning). Decentralization is best in conditions of high heterogeneity. With increased rivalry between chains, centralization performs best (see also Monge and Contractor (2003) for further details).
Stewart (2001)	Coevolving organization: a broad introduction to the *NKCS* model and its application to the structuring of business organizations, covering competition, branding, communication, knowledge management, management styles. Case studies include the UK national health service, a medical network, and telecoms.	Conceptual	Practical guidelines for managers thinking about applying the *NKCS* to their business, principally in a qualitative way, with advice to then build a computer model.

(continued)

Table 12.2 (*Contd.*)

Author	*Application*	*Research method*	*Findings and implications*
Levitan et al. (2002)	The *NKC* is used to model the web of interactions within and between groups. Attention is directed toward greater tuning of *NKC* parameters and to the temporal dimension.	Theoretical development with computer simulation	For short search periods larger organizational sizes fare better because larger interconnected groups can experiment with a larger number of initial alternatives. For longer periods smaller groups with a small number of external connections perform best as they are able to experiment and exploit random opportunities. Over time, as the number of external connections increases, then small increases to group size improve performance. In all circumstances performance is best in the complex region.
Su and Mylopoulos (2006)	The TEMPO model extends the TROPOS information system development model by adding *NKCS*-style coevolution to information systems goals. Goals in an existing information system are coupled and can coevolve with newly elicited goals such that the information system as an entity coevolves with its environment. The TEMPO model is applied to the evolution of a retail Web site and the method tested using graduate students.	Theoretical development with behavioral case study	Both novice and experienced developers in agent-oriented information systems development performed better when given a TEMPO model of the Web site. TEMPO provided a guide to developers in the evolution of more complete and higher quality information system models.
Curşeu (2007)	Complex adaptive systems theory is used to build a model of virtual team effectiveness. The strengths and weaknesses of the *NKCS* model are considered in modeling virtual team behavior and the dimensions of cognition, trust, cohesion, and conflict.	Conceptual	The author speculates that neural network models could be a more viable alternative to *NKCS* models in simulations of virtual team cognition. Neural networks would be more suitable for modeling constraints that are related to the diversity of the agents and would better capture the relationships between agents.
Vidgen and Wang (2007)	Coevolution of business processes and Web services technology. Business process management relies on invoking Web services to execute a business process. The processes and Web services have internal complexity and external linkages with each other.	Conceptual	A business process infrastructure may become chaotic if processes and Web services are simple (low *K*) but interconnected (high *C*) and freeze if they are internally complex (high *K*) but loosely coupled (low *C*) with implications for organizational agility. The role of patching and granularity of Web services and processes is considered. The *NKCS* is further advanced as a way of thinking about co-evolution of human and non-human species.
Colovic and Cartier (2007)	*NKCS* is used in a qualitative case study of exploration and exploitation in nine inter-firm networks in Japan. Individual firms were interviewed and their networks elicited (size of network and intensity of ties) and then categorized as low/high for internal and external coevolution.	Qualitative case study	Different patterns of network are identified: colony (strong internal, *K*, and strong external coevolution, *C*), herd (weak internal, weak external), pack (strong internal, weak external), and migratory (weak internal, strong external).

APPLYING AND EXTENDING THE *NKCS* TO MANAGEMENT RESEARCH

In this section we introduce an extension to the *NKCS* that has been implemented in Sendero – differential species change rates – and illustrate the findings by application to a topic of relevance to organizational and management studies, namely the development of the microcomputer industry. We take Anderson's (1995) case study of the development of the microcomputer industry as reinterpreted by Marion (1999) through an *NKCS* lens. We then show how Marion's reading of the development of the microcomputer industry can be further illuminated with an extension to the *NKCS* model, i.e. differential species evolution rates.

The microcomputer industry

The microcomputer emerged in the mid-1970s as a new configuration of existing technologies creating a new species separate from the prevailing mainframe computer. In Holland's terms this new configuration represents an aggregation; the components were in place and once they had reached a critical level could come together to create a new level of technology (Holland, 1995). Micros were cheaper than mainframes but were not a direct competitor at first as they targeted different markets – home users rather than corporations. The architectures of micros were competing with each other and in the early days of the micro there were numerous architectures, reflecting the different chip sets and a range of operating systems. This first period of the micro we label the *contagion* phase, typified by many microcomputer producers and architectures and no clear idea of who and what would prevail.

In *NKCS* terminology, the contagion phase is represented by a large number of competitors (S) with low K values. Although the early producers of microcomputers might not in actuality have been lone engineers working from their garage, these producers were typically small and were often led and managed in an idiosyncratic fashion. Initially, C coupling between the producers was low but as they found their niches, and acted to defend them from invaders, competition between them increased and thus C increased. This profile, high S and low K with C increasing over time, suggests a chaotic regime.

In 1981 IBM entered the micro market with a new operating system and quickly came to dominate in the business market. Apple was strong in the educational market and its VisiCalc spreadsheet had secured it a place in the business market. Other suppliers were working in niches, such as Commodore (popular at the low end of the market and in Europe) and Radio Shack, who sold the Tandy micro through its substantial retail network. By the mid-1980s IBM's operating system was dominant and other architectures dwindled away. The only architecture to survive with a strong market presence was Apple, who introduced the Macintosh in the mid-1980s. At this time IBM was still running the DOS operating system – a command-line driven and somewhat arcane operating system – whilst Apple had introduced its simple mouse-based system with a graphical user interface, the Mac OS. In response Microsoft introduced its Windows operating system but it took quite a few years and versions for it to match up to the simplicity and elegance of the Mac OS. The microcomputer market of the 1980s and 1990s was dominated by IBM and Apple and users were typically adherents of one or the other. IBM was the *de facto* business computer while educational users and creative business people, such as graphic designers, were the typical Apple audience. This second phase we label the *dualistic* phase.

Thus, as the number of suppliers fell and niches were built and defended, the dualistic phase came to be dominated by a small number of players (S), each of whom had increasingly large K values as their organizations grew in size and internal complexity. Users tended to be faithful to either PC or Mac and the switching costs of moving from one to the other were high, involving financial outlay (new hardware, software, and peripherals; data and applications to port; training and familiarization to undertake). The high costs of switching and the separate development of the architectures suggest a relatively low C value. The dualistic profile (low S or low C, and high K) points to an ordered regime.

In the twenty-first century the gap between IBM-architected personal computers (PCs) and Apple Macs has narrowed as the operating systems become ever more similar and applications and data are easier to port from one architecture to the other. Although IBM has now withdrawn from the manufacture of microcomputers its architecture lives on in the form of the generic PC. The distinction of PCs for business use and Macs for more creative applications still persists but the distinction is rather more blurred. Innovations in the micro industry are now incremental rather than radical, dealing with processor speed, hard drive access speeds, improvements to RAM, and peripheral technologies such as CD and DVD drives. Major innovations are less frequent and more difficult to achieve. This phase we label the *open market* phase.

In the open market phase PCs and Macs had somewhat converged such that interoperability increased (Mac programs could run on PCs and vice versa, common data formats allow data to be shared between platforms) and the switching costs became less of an issue. This suggests that C coupling is increasing as the architectures become more inter-woven, while K values are reducing as new and more agile organizations (S) find niches in the ecosystem to exploit. This reading points toward a regime that is moving toward the complex region.

Differential rates of innovation in the microcomputer industry – NKCS-R

In the base *NKCS* model each species moves at each time tick and in a generation all species in the set get the opportunity to make their move. This need not be the case: some species may be able to move faster and innovate more than others. Ahouse et al. (1992) argued that larger genomes (i.e. those with larger values of N) should take fewer steps and so explore a smaller subset of their local genotype neighborhood, i.e. species with different N would have different *relative* rates of evolution. Interesting effects have been reported by Bull et al. (2000) who allow species to move at different rates to simulate the coevolution of memes and genes. For example, species *S0* might move at every time tick while (R = 1) while species *S1* moves at every tenth time tick (R = 10), i.e. *S0* moves ten times faster than *S1*. This in effect provides a further tuning parameter, R, over and above K and C for a coevolving system (i.e. the *NKCS-R* model). This extension is likely to be particularly relevant to organizational coevolution where organizations can move and develop at different rates, reflecting, for example, differential rates of innovation in the marketplace.

Inspection of Table 12.1 and Figure 12.2 shows that the combination of C = 1 and K = 16 leads to a strongly ordered/ESS outcome (the coevolutionary sets stop walking quickly), while C = 8 and K = 2 leads to a chaotic/RQE (none of the coevolutionary sets stops walking). For C = 4 the complex regime emerges when K = 8. Thus we will use the RQE regime to represent the contagion phase, the ESS regime for the dualistic phase, and the complex regime for the open market phase of the microcomputer industry. For simplicity, we hold S = 2 and manipulate C and K to demonstrate the emergent behaviors. In each case and for each value of R the *NKCS-R* model was run ten times with ten coevolving sets (100 scenarios).

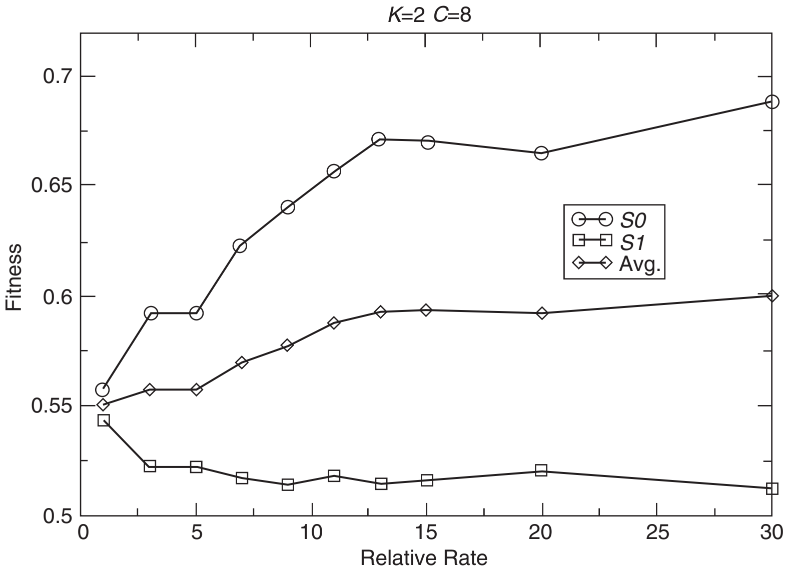

Figure 12.3 Differential rates in an RQE regime (N = 24, ten runs of ten coevolving pairs, 5000 generations)

Contagion

Figure 12.3 shows two species coevolving at different rates. Species *S0* moves on every tick and has a constant rate value, *R*, of 1. Species *S1* starts with an *R* value of 1 increasing to 30, at which point *S0* is making 30 adaptive moves for every one move of *S1*. When the standard *NKCS* model is run all the species in a coevolutionary set achieve roughly equal fitness. In the *NKCS-R* model the species start together but quickly diverge with *S0* achieving a fitness of close to 0.7, substantially higher than the starting fitness of both species of around 0.55. Interestingly, the improvement in fitness for *S0* is not mirrored by the decline in fitness of *S1* and the average fitness of the two species increases. This suggests that when the regime is chaotic there is considerable benefit to being innovative; the differential rates of movement provide a damping effect on the disturbance caused by relatively high *C* coupling. Those microcomputer producers that can move quickly are likely to be most successful.

Dualistic

Once the regime becomes ordered the story is very different (Figure 12.4). The fitness attained when both move on every tick is not substantially different from the fitness attained when $R = 30$ for *S1*. Thus, it would not seem to matter whether the PC or Mac architectures innovate faster than their competitor since the *C* coupling is low and moves by one do little to disturb the other, even after relatively long periods of inactivity.

Open market

In the complex regime (at the edge of chaos) the gain and loss are roughly symmetrical – the benefit to *S0* of moving faster than *S1* is about the same as the loss of fitness for *S1*. Figure 12.5 shows that there could be a small decrease in average fitness for the two species as a result of differential change rates.

The *NKCS-R* model provides organizations with an additional tuning variable over and above *K* and *C*: *R*, the rate of movement on

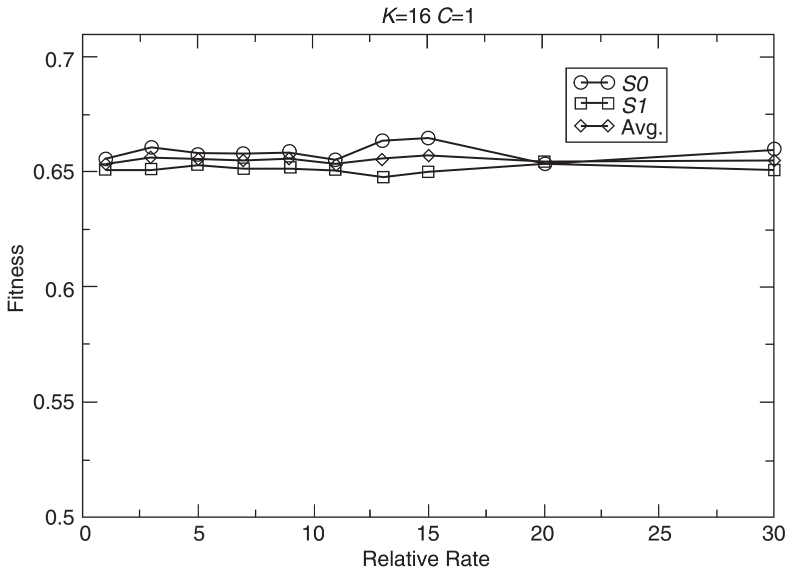

Figure 12.4 Differential rates in an ESS regime (N = 24, ten runs of ten coevolving pairs, 5000 generations)

the landscape. In chaotic environments, such as those typical of emerging industries and periods of disruptive change the benefits of moving faster than competitors are substantial and improve the average fitness of the industry overall. In ordered regimes, such as an established industry with a small number of large (high *K*) players with well-defined market niches (low *C*) the benefits of innovation are likely to be low, at least until the time that a new and disruptive technology makes an appearance. Where the industry is in the complex region then gains by one party are offset by losses in a coupled species and it is best for the industry if species' moves are coordinated.

Our reading of the microcomputer is based on mutualism and competing species; a similar reading can be made for symbiotic configurations such as the alignment of a firm's business strategy and IT strategy (Chan and Reich, 2007). For example, our analysis would suggest that for a firm working in the chaotic region overall fitness would be greater for that firm if the rate of innovations made by the IT organization were constrained (Figure 12.3). Where the firm is characterized by stasis then the implication is that the effectiveness of innovations made by the IT organization will be overwhelmed by the internal complexity of the business, *K*, and the intra-organizational complexity, *C*, between business and IT (Figure 12.4).

CONCLUSIONS AND FUTURE DIRECTIONS

The *NKCS* is often used in an abstract way, where researchers describe the *NKCS* model and then show how it might be applied in a particular domain (e.g. Baum, 1999; Vidgen and Wang, 2007). Other researchers take the basic *NKCS* implementation and extend it (e.g. Bull et al., 2000; Chang and Harrington, 2000) and report the results from their software simulations. These simulation studies should follow a research method, such as that identified by Davis et al. (2007), who recommend a process that runs through: the selection of an intriguing and simple research question, the selection of a simulation approach (e.g. the *NKCS* model), the creation of a computational representation (e.g. Sendero), verification of the computational representation (e.g. benchmarking of results), experimentation to build novel theory, and finally, validation with empirical data. However, research that adopts the *NKCS* and uses empirical data is sparse. Indeed, we found only one example of *NKCS* research that used empirical data – and in that instance the *NKCS* was used in a qualitative way (Colovic and Cartier, 2007). Although there is value in framing the relevance of *NKCS* in different domains and applications, and in extending the model to make it more realistic for social science research, there is significant scope for coevolutionary researchers in applying the *NKCS* in practice within an organizational setting (Braa and Vidgen, 1999). In an organizational setting the *NKCS* can be used:

- in a descriptive way (how well does the *NKCS* explain empirical evidence?)
- in a qualitative way (what can we learn about organizations and how to manage them through the lens of coevolution?)
- in an interventionary way (how might we use the *NKCS* to guide change?)
- and for prediction (how well does the *NKCS* fit observed behavior and what is its predictive power, if any, in statistical terms?)

Finally, a major limitation of the *NKCS* is that it operates at a single level. Coevolution is a multi-level process and Lewin and Volberda (1999) list multilevelness/embeddedness as a core requirement for conducting coevolutionary research in organizations. They argue that coevolutionary effects take place at multiple levels, within firms as well as between firms. They also note that most research is either at the population level focusing on macroevolutionary theory of the firm or at the microevolution, intra-firm level investigating capabilities and competencies of the individual organization in its competitive context (p. 526). McKelvey (1999) asserts that coevolution at lower levels occurs in the context of higher levels of coevolution. Multi-level, emergent, and recursive implementations of the *NKCS* are a major challenge for researchers wishing to apply coevolutionary ideas in an organizational and social context.

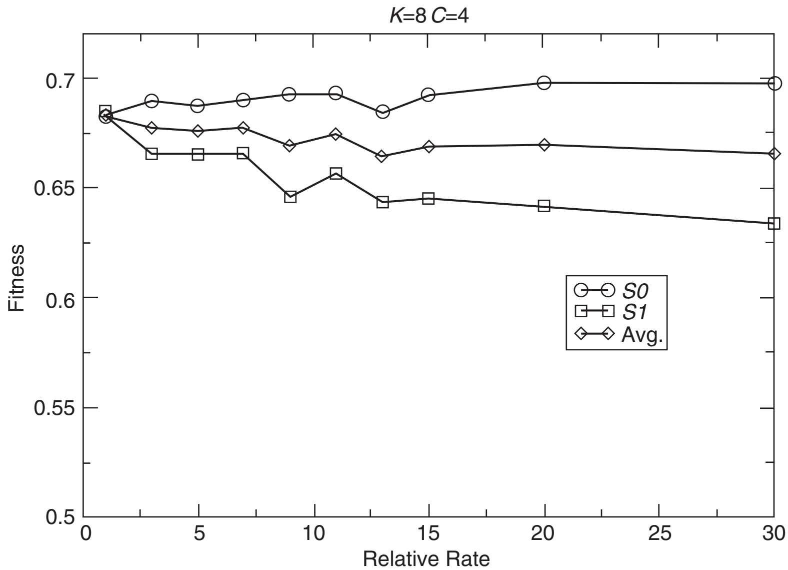

Figure 12.5 Differential rates in the complex region (N = 24, ten runs of ten coevolving pairs, 5000 generations)

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13

Using Genetic Algorithms to Model Strategic Interactions

William Martin Tracy

> There is a fairly close analogy between the earlier stages of economic reasoning and the devices of physical statics. But is there an equally serviceable analogy between the later stages of economic reasoning and the methods of physical dynamics? I think not. I think that in the later stages of economics better analogies are to be got from biology than from physics; and consequently, that economic reasoning should start on methods analogous to those of physical statics, and should gradually become more biological in tone.[1] (Alfred Marshall, 1898)

The use of Genetic Algorithms (GAs) in strategic modelling constitutes a promising application of complexity tools to the field of management. There are at least two benefits to modelling strategic interactions with GAs. First, unlike analytical models, GAs allow researchers to observe the modelled systems' dynamic, disequilibrium behaviour (Holland and Miller, 1991). This is particularly important for strategists, as corporate strategy is most useful when a firm's external environment is in a state of disequilibrium. Modelling this disequilibrium is even more important for strategists if strategies employed during the disequilibrium period can effect the eventual equilibrium selection. Second, there are reasons to believe that GA-based models might be better predictors of human and firm behaviour than classical game theory analytical models.

This chapter is organized as follows. First, I explain genetic algorithms and provide an example of a GA-based strategic model. The next section traces out the history of thoughts that underlie the application of GAs to strategic analysis. The third section examines the process validity of GA-based models. In other words, the third section describes why the mechanisms of a GA-based model reflect the processes real world decision makers use to select strategies. The fourth section of this chapter surveys the existing research applying GA-based models to strategy. The final section outlines future directions for the application of GA-based models to strategic analysis.

AN INTRODUCTION TO GA-BASED MODELS

GA-based models of strategic behaviour are a refinement of the game theoretic approach to strategic modelling. Both classical game theoretic models and GA-based models of strategic interaction consider the behaviour of economic agents. However, there are some key differences between these approaches. Game theoretic models focus on hyper-rational homogeneous agents. GA-based models consider the heterogeneous actions of moderately intelligent agents.

In orthodox game theory, the researcher typically assumes that all agents are intellectually capable and employ their intelligence in a similar fashion. Indeed, most classical economic models assume that if two agents have the same resources, and the same information, they will behave identically. This conceptual focus on the similarities across agents often allows a modelling focus on the behaviour of a single representational agent. Many game theoretic models also assume each agent knows all of its opponents employ the homogeneous, profit-maximizing, brand of rationality. With such assumptions, the modeller can apply logical deduction to refine the set of possible outcomes.

In contrast, the GA approach emphasizes the differences among agents. GA-based models explicitly consider many agents even if all the agents face the same problem, have the same level of intelligence, and are choosing from an identical set of strategies. As such, GA-based models can be considered as being a part of the Agent-based Modelling approach. The need to model many agents in a GA-based model stems from this approach's treatment of agent intelligence. Unlike the game theoretic approach, GA-based models do not assume that individual agents are hyper-intelligent and hyper-rational. Rather, GA-based models assume that agents who experience relatively poor outcomes might copy the strategies of more successful peers. This process of stochastically adopting the strategies of more successful peers eventually enables a population (or a system) of agents to evolve quite sophisticated strategies.

Genetic Algorithms are a computation technique used to operationalize this stochastic emulation process. Introduced by John Holland (1975), GAs evolve a population of agents. Each agent is primarily defined by a set of rules.[2] The rules govern the agent's behaviour. During the course of a generation, some measure of fitness is associated with each agent in the population. A stochastic selection of the fittest mechanism and basic genetic operators are used to populate the successive generation with agents. Much as natural Darwinian evolution produces increasingly fit species, the GA evolves increasingly fit agents.[3]

Each agent's rules condition the agent's behaviour on the state of the external environment. Hence, each agent's behaviour is dependent on what is going on around the agent. In models of strategic interaction, the state of the environment is often a function of the past behaviour of other agents. The agents' rules can be understood as actions associated with a simple classification scheme; *if the world is in state Y, execute action Z; if the world is in state X, execute action W.* In GA-based strategic models, the complete set of rules typically assigns a behaviour to every possible state of the world. The representation of the agent's rules is called a chromosome. The chromosome is structured to allow for the genetic operators such as crossover and mutation.

In a simple GA the chromosome is often a finite string of zeros and ones. Such a chromosome could determine how an agent makes a 'yes' or 'no' decision. A mapping scheme associates a state of the world with each bit in the string. These bits are typically called genes. Figure 13.1 displays an example chromosome-mapping scheme for an Iterated Prisoners' Dilemma (IPD) game in which an opponent's last three decisions impact the agent's current behaviour.

In a single stage Prisoners' Dilemma game, each player must decide whether to cheat or cooperate with the other player. If one player cheats and the other cooperates, the cooperating player obtains a very poor outcome, and the cheating player achieves a very good outcome. If both players cheat, both obtain relatively poor outcomes. If both cooperate, both obtain a moderately good outcome.[4] In an IPD game, a set of players repeat the

Gene Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Gene Value	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?
Opponent's History	*	c	d	c	d	c	d	c	d	c	d	c	d	c	d
	*	*	*	c	c	d	d	c	c	d	d	c	c	d	d
	*	*	*	*	*	*	*	c	c	c	c	d	d	d	d

Figure 13.1 Sample rule codification scheme

interaction and can condition their behaviour on their opponent's past behaviour.

In this example, the rule governing agent behaviour is defined as a 15-bit binary string. Each gene in the bit string follows a particular three-stage history. In Figure 13.1, each gene is represented by a '?'. In an actual agent, however, each '?' would be either a '1' or a '0'. According to Figure 13.1, the first gene determines how the agent behaves the first time the agent encounters a particular opponent. If the value of the first gene is a '1', the agent cheats in the first round. If the value of the first gene is a '0', the agent cooperates in the first round. The second gene determines how the agent will behave if the opponent cooperated in the first round. The third gene determines how the agent will behave if the opponent cheated in the first round, and so on. After the first three rounds, this scheme truncates the history used by the agent. In the 48th round, an agent will only consider what the opponent did in the 45th, 46th, and 47th rounds. If an agent's opponent cheated in the 45th round, but cooperated in the 46th and 47th rounds, then the value of the 12th gene will determine the agent's behaviour in the 48th round.[5]

Figure 13.2 displays the typical flow of a one-population genetic algorithm. In the example above, the GA's fitness function would be based on the IPD game. Following the conventions of game theory, this fitness function can be operationalized by assigning a pair of utility-based payoffs to each outcome.[6]

As Figure 13.2 shows, the population used in the first generation is typically drawn at random. If there are 20 agents in the population, the GA will start by generating 20 random rules, or chromosomes. Each of these chromosomes will be a 15-bit binary string. To assign a fitness score to each agent, the agents will be broken into pairs. Each of the 10 pairs of agents will play a fixed number of rounds of the IPD game. Each agent's fitness will be the sum of the payoffs that the agent earns in all the rounds played in a generation.

Once each agent has a fitness score, a stochastic 'selection-of-the-fittest' sub-mechanism is used to select parents for the next generation. Three-agent tournament selection is a common selection sub-mechanism. Under this mechanism, three agents are drawn from the population at random. The drawn agent with the highest fitness score is selected as the first parent. This tournament-based, parent-selection process is repeated to select a second parent. The chromosomes of the two parents are combined to create a child agent.

Two genetic operators are used to add stochastic variation to the child agent; crossover and mutation. Crossover takes place in between two genes. The crossover point is randomly chosen between any two genes in the chromosome at random. All genes before the crossover point come from the first parent. All genes after the crossover point come from the second parent.[7] Next, mutation alters some of the genes. Genes subject to mutation are selected at random and their

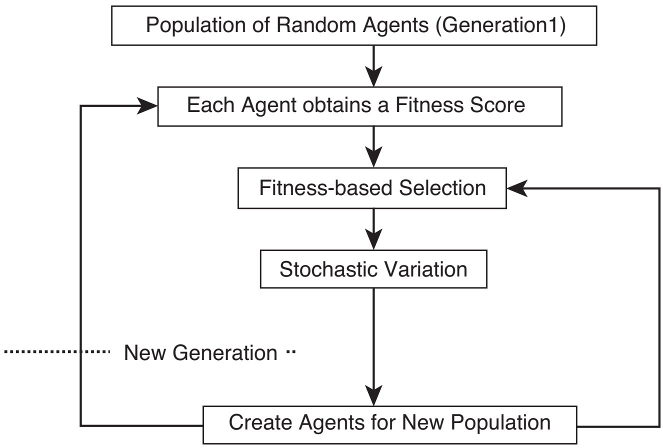

Figure 13.2 Flow of a typical GA

value is 'flipped'. For example, if the initial value of a gene selected for mutation is originally '0', the value of that gene will be '1' after mutation.[8] This parent-selection/child-production process is repeated, with replacement,[9] until the number of agents in the child generation equals the number of agents in the parent generation. Once the next generation of agents are created, the entire process is repeated. This continues for as many generations as the researcher wishes to conduct the experiment.

It should be emphasized that the parameters and evolutionary sub-mechanisms used in the above example are for illustrative purposes, and are not intrinsic to the definition of a genetic algorithm. A far more complete introduction to GAs can be found in Melanie Mitchell's *An Introduction to Genetic Algorithms* (1996).

THE INTELLECTUAL HISTORY OF GA-BASED STRATEGIC MODELS

GAs were originally employed as optimization techniques, and were primarily used to locate near-optimal solutions to difficult problems, such as the travelling salesperson problem. GAs have also been used as a 'black-box' optimization process in the economic and management literatures.[10] A second stream of strategy research uses GAs to *model* strategic interaction. This second stream of research appeals to biology in order to build social science models. This heterodox appeal to biology is best understood in contrast to the orthodox approach to economics, which primarily appeals to Newtonian physics.

The application of Newtonian physics to strategic interactions dates back to Cournot (1838). Cournot's approach was itself considered heterodox for decades. With the rise of Walrasian economics, Cournot's approach began to gain some prominence. During the twentieth century, Newtonian techniques dominated the economic orthodoxy. In order to justify the use of methodological techniques borrowed from Newtonian physics, twentieth century economics assumed near-perfectly rational, profit-maximizing agents.

Armen Alchian (1950) challenged that dominant economic dogma by asserting that a firm's profit maximizing *intentions* are irrelevant to the firm's success. Instead, Alchian proposed that *realized* profits determine a firm's likelihood of survival. Alchian further asserted that realized profits are as much a function of chance as planning. 'Even in a world of stupid men there will still be profits', noted Alchian. To Alchian, the most profitable firm does not need to implement the perfect business model; it merely needs to implement a business model superior to the models of its competitors. The more uncertain the world, the more luck, and not rational planning, determines profitability.

Although luck is important in Alchian's views of firm and market behaviour, he strenuously asserts that, on aggregate, industry behaviour is not random. Through a process similar to Darwinian evolution, a population of increasingly competent agents will emerge. Alchian made the analogy to evolutionary operators explicit by noting that 'the economic counterparts of genetic heredity, mutations, and natural selection are imitation, innovation, and positive profits'.

Alchian's analysis in this area was mostly based in qualitative analogies. Quantitative models applying these principals began appearing in the early 1980s. Invoking (i) the evolutionary logic of Alchian (1950) and (ii) the theoretical premises of Schumpeter's dynamic superstructure of an economic system (Schumpeter, 1934), Nelson and Winter (1982) proposed using finite Markov chains to model the evolution of firms' routines. Although they discussed the absorptive states that might serve as equilibria for such models, Nelson and Winter also posited that such an approach might provide insight on an economic system's dynamic, disequilibria behaviour.

Like the models introduced by Nelson and Winter, GAs are a class of finite Markov chains (Goldberg and Segrest, 1987). Also, like the models introduced by Nelson and Winter, most work uses GAs to model a system in which firms' strategies or routines evolve. The method of codifying agent rules (e.g. routines), however, typically differs between the two approaches. Additionally, while the Nelson and Winter approach placed a great emphasis on individual agent search, the GA-based approach puts more emphasis on imitation.[11]

PROCESS VALIDITY AND GA-BASED MODELS

It is fruitful to model strategic behaviour with a GA if (and only if) the strategy updating mechanisms used by real-world agents are sufficiently similar to the evolutionary process in the GA. Behavioural game theory has recently started to focus on how players use the limited information they are provided with to update their strategies. Traulsen et al. (2010) suggest that when players can ascertain the strategies employed by peers and the payoffs associated with those strategies, they initially copy the strategy of the most successful peer they can observe over 60% of the time. The propensity with which the most successful strategy is copied (or maintained), however, increases as the experiment continues, reaching more than 80% after 25 rounds. The authors of this study interpret the remaining instances of strategy updating to represent random experimentation, or mutation. These findings are parsimonious with the strategy updating sub-mechanisms embodied in GA-based models with tournament selection, and moderate levels of mutation.

In addition to data from behavioural experiments, justification for a GA-like, evolutionary approach to strategic updating can also be found in case studies. One particularly compelling example comes from the online social networking industry. In the summer of 2008, social networking site MySpace was the most popular website in the United States, boasting more page views than Google.[12, 13] The first mover in this market, Friendster, originally dominated the social networking space. By the summer of 2008, however, MySpace had more than three times as many unique monthly visitors as Friendster.[14]

According to a recent history of MySpace (Angwin, 2009), its creators explicitly set out to imitate Friendster. Like the many Friendster copycats who entered this industry, MySpace consciously altered a few aspects of Friendster's model. For example, MySpace allows 'fake' identities, while Friendster attempts to force users to verify their own identity. MySpace's most significant alteration to the Friendster model, needless to say, was accidental. MySpace was originally coded in a computer programming language called Pearl. One month after the site launched, the company's Pearl expert quit. Rather than hire a new Pearl expert, the company hired an engineer to replicate the software in a programming language called ColdFusion. The ColdFusion coders forgot to add code to prevent users from uploading markup languages, such as HTML, in the user comment sections. This constituted a major security flaw, but before the company could block the use of markup language, young tech-savvy users began uploading HTML to alter the appearance of their MySpace page. As Angwin noted, 'Suddenly teenage girls could decorate their MySpace page with hearts and glitter and smiley faces the same way they decorate their lockers and book bags'.[15] This feature proved popular with younger users and fuelled an early boost in MySpace's subscriber base. As MySpace began to grow its subscriber base, it also attempted to blend successful aspects of other internet-based business models into its operations. For example, after viewing the success of HotOrNot.com, MySpace added a similar feature called Hot or Cold.

The process through which MySpace developed its business model and beat out Friendster closely follows the sub-mechanisms that drive a GA. A GA's fitness-based selection can be understood as a firm's imitation of more successful, or fit, peers. At MySpace's inception, Friendster had achieved a large number of subscribers and a high level of venture capital. This signalled that the Friendster's strategy was 'fit', and should be imitated by new entrants. A combination of total venture capital funding and number-of-subscribers is a suitable fitness metric in the early online social networking industry, and other industries dominated by internet start-ups. A combination of profits, earnings, and stock performance, instead, might be a more suitable fitness metric for more mature industries.

The GA's crossover operation represents the processes through which a less successful firm combines the strategies of two or more successful incumbents to create a new strategy. In the MySpace example, crossover can be understood by the blending of the functionality from HotOrNot.com into the Friendster model.[16] More generally, crossover represents a process's partial imitation. Management consulting firms and business schools facilitate this type of partial imitation by drawing 'lessons' from evolutionarily fit firms. These lessons are typically a set of routines that other firms are encouraged to adopt to improve their performance. In the GA-based models, routines selected for partial emulation are chosen at random. In contrast, when selective emulation is employed in the real world, a logical argument is typically offered to support drawing a particular lesson from a successful firm. However, the validity of such logic can only be ascertained *ex post*. There is enough error in the identification of helpful routines that operationalizing selective emulation at random should constitute a reasonable approximation of the actual mechanism in the real-world system. For example, as late as January 2001, many business school professors still extolled the *positive* lessons one could learn from Enron. It is now clear that Enron's outstanding financial performance in late 2000 and early 2001 was driven by fraud, not the 'best practices' that MBA students were taught at the time. Although this is an extreme example, it supports the notion that, at the system level, the selection of lessons, or sets of routines, from successful peers can be modelled with random selection.

Mutation can be understood to represent small modifications to strategy. It is easy to see how mutation represents the unintentional deviations from the target business model, such as MySpace user's ability to upload mark-up language. However, mutation can also be understood to represent conscious changes to the target strategy, such as MySpace's decision to allow fake identities. The intuition behind this interpretation invokes Alchian's (1950) arguments concerning the role of luck in determining firm performance. At the time of MySpace's launch, there was genuine uncertainty regarding which suite of features would be most appealing. All entrants into the online social networking space could produce logic asserting that their company's suite of features was optimal. MySpace's logic can only be validated *ex post*. *Ex anti*, a system-level model with a sufficient number of agents can treat both unintentional and intentional deviations at random.

CURRENT USES OF GAs IN STRATEGIC MODELLING

Strategic game theory was the first managerial sub-field to build models with genetic algorithms. These models highlighted the co-evolution of agents competing against each other, and compared the results to game-theoretic predictions. Co-evolutionary GAs typically exhibit a high degree of stability around Nash Equilibria (NE). However, in some situations where human behaviour deviates from the predictions of game-theoretic NE, GAs have displayed limited success in predicting the deviations.

In 1987, Robert Axelrod used GAs to co-evolve a population of agents that played the Iterated Prisoner's Dilemma (IPD) (Axelrod, 1987). Axelrod observes that these populations frequently converged to a Tit-for-Tat strategy, with the phenotypical outcome of 'always cooperate'. Although the codification scheme Axelrod uses is more complex than the example at the start of this chapter, my example captures the approach Axelrod took.

The game theory community largely misinterprets Axelrod's work by assuming that Axelrod supports 'always cooperate' as the stable outcome of a *finite* IPD. However, Axelrod's model actually examines an indefinite IPD. Axelrod's work eventually leads to a realization that co-evolutionary GAs often evolve strategies that lead to game-theoretic NE. Significant subsequent work uses GAs as a black box technique to locate NE.[17]

Dawid (1999) provides a more detailed account of the relationship between NE and the solution space of simple co-evolutionary GAs. Dawid's study focuses on NE as Evolutionarily Stable Strategies (ESS). John Maynard Smith (1982) defined an ESS as being a strategy that, 'if all the members of a population adopt …, then no mutant strategy could invade the population under the influence of natural selection'. To apply the ESS concept to co-evolutionary GAs, Dawid modifies this definition by asserting that a mutant is 'most probably repulsed … if the number of mutants is sufficiently small'. By (a) restricting his analysis to a limited subset of selection and mutation rules, (b) approximating the behaviour of the Markov process with difference equations, and (c) focusing exclusively on cases with genotypical convergence, Dawid is able to examine which convergent ESS attracts the dynamic co-evolutionary system and which repels it. While some non-NE are asymptotically stable under certain crossover operators, only pure NE are stable under all crossover operators. He also shows that pure NE are asymptotically stable with respect to mutation.

Dawid supports his theoretical findings with numerous simulation experiments. He notes that GAs cannot locate the mixed NE associated with circulant payoff schemes. He also observes that if the mutation is set to zero, GAs cannot converge to pure NE in so-called 'deceptive games'. However, Dawid concludes that 'in most cases, where no circulant or misleading best-reply structure occurs, the GA has no problems in reaching one of the Nash equilibria'.[18]

There is some evidence suggesting that in games with multiple NE, GAs can further refine the equilibria selection. Arifovic (2001) applies a co-evolutionary GA to an iterated tacit cooperation game to observe the system's transitions between the various NE. She concludes that the GA can be induced to reach any NE in that game; however some NE are persistently more stable than others.

There is a wealth of experimental game-theoretic work revealing a disconnect between human behaviour and game theory's predictions (e.g. McKelvey and Palfrey, 1992; Hoffman et al., 1996; McCabe and Smith, 2000; Alvaed, 2003; Colman, 2003; Henrich and Smith, 2003; Hill and Gurvan, 2003; Tracer, 2003. In some of these cases, genetic algorithms have been shown to deviate from the game-theoretic prediction in ways that mirror the deviations of actual human agents. Two important papers in this area are Andreoni and Miller (1995) and Ünver (2001).

Andreoni and Miller (1995) apply co-evolutionary GAs to the auctions detailed in Kagel and Levin (1986). As in Kagel and Levin's human experiments, the computational experiments in Andreoni and Miller show evidence of 'the winner's curse', which is a deviation from the predictions of the standard, game-theoretic, risk-neutral, Nash equilibrium. This work suggests that while co-evolutionary GAs are drawn towards NE, they also deviate from NE in a way that reflects the behaviour of real economic actors.

Ünver (2001) also shows evidence that co-evolutionary GAs can marginally out-perform game-theoretic induction in predicting the stability of entry-level, medical job matching schemes. Ünver's work extends Roth's (1991) game-theoretic work, which analyzes the pairwise stability of matching mechanisms.

During the 1960s, the UK labour market for new physicians experienced a time-based unravelling; in an effort to secure better doctors, and better appointments, hospitals and medical students entered into binding contracts earlier and earlier in the medical school process. This resulted in sub-optimal matchings, because both parties entered the binding contract before they had full knowledge of their options. Starting in the late 1960s, the UK's National Health Service began implementing voluntary matching schemes at the regional level. Some of these schemes worked and prevented unravelling. Others collapsed, and were either discontinued or replaced with a scheme that worked.

Alvin Roth (1991) uses game compliance with game theory's incentive-compatibility constraints as a criterion to evaluate the various schemes implemented in the UK. Roth discovers that all the schemes collapsing in real life failed to meet the incentive-compatibility constraints. However, two of the schemes that survive also fail to meet the incentive-compatibility constraints. Human subject behavioural work by Kagel and Roth (2000) confirms performance differences between the non-incentive compatible schemes that persist in real life and those that collapse in real life. From this we can conclude that the game theoretic notion of pairwise stability miscategorizes functioning mechanisms as unstable

In 2001, Ünver used a multi-agent, co-evolutionary GA to compare the non-incentive compatible schemes that collapsed with those that persisted. The earlier agents entered into a binding contract, the higher the simulated social cost associated with that scheme. This embodies the notion that earlier matches are less efficient because the student's true potential has not yet been revealed. Over multiple runs, Ünver found that the non-incentive compatible schemes that persisted had marginally lower cost than the mechanisms that collapsed. These experiments have led to continued use of co-evolutionary GAs in the analysis of other entry-level labour mechanism design problems (Haruvy et al., 2006).

There are a large number of papers employing GAs to analyze game-theoretic problems. The above is intended to highlight the important developments in the field, rather than provide an exhaustive list. Taken as a whole, the current state of work in this area suggests that GA-based models typically replicate the results of analytical game-theoretic models. However, in some cases where analytical game theory is a particularly poor predictor of human behaviour, the predictions of GA-based models differ from their analytical game-theoretic counterparts. This strongly suggests a greater future role in the use of GAs in strategic modelling and analysis.

The existence of phenomena that can occur in a GA-based model but not in a more analytic treatment of evolution might explain the instances in which GAs outperform more traditional game-theoretic models in prediction. For example, a process akin to genetic drift has been observed to push GA-based models out of a sub-game perfect equilibrium (Harrald and Morrison, 2001; Eaton and Morrison, 2003; Tracy, 2008). Conversely, this genetic drift is not observed in traditional game-theoretic models. Such phenomenon might enable GA-based models to account for possibilities that cannot occur in more analytical models.

FUTURE DIRECTIONS

This chapter argues that the process through which real-world agents update their strategies often resembles the GA process. This suggests that GA-based models may be more insightful than traditional analytic models, which typically embody a lower degree of process validity.

Most work applying GAs to strategic game theory focuses on comparing the ESS selected by a GA to the equilibrium identified by game-theoretic solution concepts, such as the Nash Equilibrium. As discussed above, the ESS identified by GA-based models are often identical to the equilibria identified by classical game theory. However, there exist some cases in which the outcomes of GA-based models differ from game theory but more accurately reflect human behaviour (e.g. Andreoni and Miller, 1995; Ünver, 2001; Casari, 2004). These results suggest an increased role for GA-based models in the analysis of strategy interactions.

There are at least two areas in which the application of GA-based models to strategy should progress over the next several years. First, the scope of strategic problems addressed with GA-based models should be expanded. For example, such an expansion could entail using GA-based models to explore the impact imitative learning on the decision to allow individual units to independently learn strategies. Second, GA-based models should be refined to the point at which they can make meaningful predictions about a system's *dynamic* response to a novel stimulus. For example, GA-based models could help us understand how a new regulatory policy will impact the competitive dynamics of an industry.

Scope of GAs in strategy

The preponderance of works applying GA-based models to strategy, focus on game-theoretic questions. However, in other managerial fields, computational models are used to understand the impact of different processes in managerial and economic systems. This is particularly true in the study of organizational behaviour.

Computational modelling has a rich history in the field of organizational behaviour, dating back at least to Cohen, March, and Olsen's Garbage Can Model (1972). There are many approaches to computational modelling in organization theory. March (1991) used a computational model to examine the link between rates of social learning and the trade off between exploration and exploitation. Other researchers interpret the information flow along a network to draw conclusions about organization structure (e.g. see Carley, 1991). Others examine how different structures affect search over topologies with varying levels of epitasis (e.g. Levinthal, 1997; Siggelkow and Levinthal, 2003).

Models based on GAs are less common in computational organization theory than other types of computational models (Davis et al., 2007). However, the limited organization theory research that does build models based on GAs are less rigid than game-theoretic models. Bruderer and Singh (1996) use a GA-based model to assert the potential coexistence of firm selection at the industry level and routine adaptation at the firm level in the determination of organizational forms. Miller (2001) uses genetic algorithms to explore the link between the depth of information processes in an organization and the number of problems the organization must solve.

Despite the limited work using GAs in organization theory, strategy research could profitably borrow from computational organization theory's experience. For example, many organization theory papers modify a model's mechanisms to correspond with differences in the real underlying generative mechanism being studied. One paper already employs this approach in the field of strategy. Lee et al. (2002) employ a GA-based model to determine the preconditions under which a population of firms will segment into distinct strategic groups. Specifically, Lee et al. (2002) treat strategic groups as an emergent phenomenon, whose existence is associated with particular attributes of the various fitness functions. These fitness function attributes are intended to represent various aspects of competition in different industries (e.g. mobility barriers, strategic interactions, etc.). The greater focus on the meaning of particular sub-mechanisms in a GA-based model (e.g. the fitness function) and the expansion beyond game-theoretic problems are important areas of future GA-based strategy research.

Sub-mechanism selection and dynamic reactions to novel stimuli

Currently, GA-based strategic models are used to help us understand emergent phenomena observed in real-world systems of strategic actors. For example, GA-based models help us understand the winner's curse (Andreoni and Miller, 1995) and the survival of unstable pairwise matching schemes (Ünver, 2001). More generally, GA-based models also help us understand the dynamic process through which some strategic systems arrive at a Nash Equilibrium. Importantly, GA-based models show a dynamic process through which a NE can be reached even if the original assumptions used to justify Nash Equilibrium do not apply. While this is useful in its own right, policy makers and social scientists are always seeking tools that will enable them to form reasonable hypotheses regarding the dynamic response of complex social systems to novel stimuli. In these cases, the dynamic, pre-equilibrium behaviour of the system is likely to be of as much interest to the researcher as the long run equilibrium.

The following three-part process can help researchers build GA-based models that generate reasonable hypotheses about how a real-world system of strategic actors will respond to a novel shock. First, the researcher should determine whether evolution could possibly drive the strategic updating for the agents in question. Next, the researcher should identify the most likely sub-mechanism and bind the parametric specifications. Finally, the researcher can test the responses of the likely model to the stimuli.

Determine whether evolution can possibly drive the dynamics of a real-world system

The usefulness of a GA-based model depends upon the extent to which evolutionary-like processes actually drive strategy acquisition in the system being examined. For example, consider a firm trying to commercialize a radically new technology without a clear set of peers to emulate. In this case, it is unlikely that a model based on emulation of more successful peers (such as the GA-based models discussed in this chapter) will be a useful platform for either existence proof testing or hypotheses generation. A model that learns from its own experiences might more fruitfully represent such a firm. Examples of these types of models include Learning Classifier Systems and reinforcement learning models.

There are many cases of strategic updating that are most likely driven by an imperfect, peer-emulation based mechanism. LeBaron and Yamamoto (2010) provide evidence that financial traders use this type of strategy updating in an order-driven market similar to the London Stock Exchange. Their method is illustrative. First, they identify a number of irregularities in the real world, order-driven market data that are ill explained by mainstream finance theory. These statistically defined irregularities can be considered as emergent phenomena. Then they identify a GA-based model that can replicate these irregularities. From this, they conclude that an emulation-based mechanism is a *possible* driver of strategic updating among traders in such markets.

An Automated Non-linear Tests (ANTs) algorithm (Miller, 1998) can be used to search for sets of parameters and sub-mechanisms that replicate real-world results. Here, an ANTs algorithm is simply a second GA 'top-level' that searches the parameter space of the GA-based model. In this case, the chromosome of the top-level GA specifies the parameters and the sub-mechanisms used in the underlying model. The fitness function for the ANTs algorithm is inversely related to the distance between the model's results and the results observed in the real world. That is, if a particular set of parameters and sub-mechanisms cause the bottom-level model to produce results that are 'close' to the real-world results, the fitness associated with that model's specification is high. Conversely, if a particular specification of the bottom-level model produces results that are 'far' from the real-world results, the fitness associated with that model's specification is low. Sub-mechanisms in the model, such as whether to use a roulette-wheel or a tournament based parent selection process, can be parameterized so that these structural choices can be included in the ANTs algorithm's search.

Identify the most likely sub-mechanism and parametric specifications

Even when the real-world agents being modelled actually update their strategies through the imperfect emulation of more successful peers, improper selection of parameters and sub-mechanisms in the GA-based model can limit the model's usefulness. Currently, most GA-based models use sub-mechanisms promoted in literature that are oriented towards using GAs to quickly find near optimal solutions to difficult optimization problems. The selection of these sub-mechanisms, and their parameters, can have a significant impact on the dynamic behaviour of the GA-based model. This is particularly true of co-evolutionary models in which multiple populations evolve in competition with each other. The relevance of a model's behaviour is likely tied to the extent to which these sub-mechanisms reflect the actual mechanisms in the real world. This is not to say that the level of detail in a GA-based model should be increased. Rather, modellers should consider carefully their choices of sub-mechanisms.

The ANTs algorithm analysis discussed above is also useful in focusing the researcher's attention on the sub-mechanisms that appear most likely given the available data. Typically, however, there is not enough data to assert a single set of sub-mechanisms and parameters. Behavioural experiments and case studies can aid in the selection of these sub-mechanisms and parameters. Again, if the insights gained through behavioural experiments and case studies lead a researcher to conclude that the real-world agents being modelled do not update their strategies through the imperfect emulation of more successful peers, then the researcher should consider other types of models.

It is worth noting that when GAs have proven most useful in explaining and/or foreshadowing human behaviour, the sub-mechanisms operating in the real world naturally resemble the sub-mechanisms borrowed from the optimization GA literature. Consider Ünver's GA work which models the efficacy of schemes designed to match recent professional school graduates with jobs. His GA-based model outperforms the analytical game-theoretic approach.

University students update their strategies through the imperfect emulation of more successful, senior peers. Members of one graduating class often copy strategies employed by successful members of the previous graduating class. These agents are likely to copy complete 'genotypical' strategies, not just observed phenotypical behaviour: consider the role that career centres, clubs, sports teams, social organizations, and informal friendships play in facilitating the process through which successful upperclassmen describe their complete strategies to underclassmen. Anyone who has repeatedly taught the same undergraduate course at a university with an active Greek life has heard their students remark that an older sorority sister or fraternity brother told them that X, Y, or Z is required to get a good grade in your course. As in an optimization oriented GA, there are distinct generations in a university setting; every year, a class enters together while a different class graduates together. The similarities between this type of real world mechanism and the mechanisms of a common GA help explain why Ünver's model (2001) is more successful than game theory at predicting the efficacy with which voluntary-match schemes pair graduating students with available jobs.

Even when real-world agents update their strategies through the imperfect emulation of more successful peers, the different generations might not be as distinct as they are in the university setting. Finance is an area well suited to GA-based models (LeBaron, 2006). As in the university setting, there is reason to suspect that investors copy complete 'genotypical' strategies and not just the observable 'phenotypical' strategies; the financial press typically publishes and promotes complete trading strategies, not one-off decisions about a particular trade. However, there is no reason to believe that trading strategies are updated in discrete generations. Indeed, LeBaron and Yamamoto (2010) present evidence suggesting that a non-discrete generation updating sub-mechanism might generate more accurate models of trading behaviour. This type of sub-mechanisms refinement should increase the efficacy with which GA-based models predict the dynamic behaviour of actors in real-world strategic systems.

Testing the model's responses to novel stimuli

Based on behavioural research, case studies, and the results of the ANTs algorithm a researcher should select the most likely set of parameters and sub-mechanism for the model. The resulting model can then be subjected to novel stimuli or shock. Once the response of this model is analyzed, a second ANTs algorithm may be used to determine if any combination of other likely sub-mechanism or parametric settings will produce a qualitatively different response. Often, a researcher may wish to compare the outcome of different stimuli. This might be useful for a firm considering a new strategy or a policy maker considering a new regulatory scheme. Again, the researcher should not focus exclusively on one set of sub-mechanisms and parameters, but should test combinations. This exercise should generate hypotheses about what might happen if a real-world system of strategic agents responds to novel stimuli.

NOTES

1 Marshall (1898: 39).

2 An alternative approach separates the strategies from the individual agents. See Alkemade et. al. (2006) and Waltman and Van Eck (2009) for a robust discussion of this alternative.

3 Because these models are stochastic, it is possible for the agents in one generation to be less fit than the agents in the previous generation. This is particularly likely after a population has converged around a local optimum in the solution space. However, the evolutionary process is generally conceived of as increasing agent efficacy, at least in the early generations of the model.

4 Although subjective terms, such as 'moderately good', 'very poor', etc., are used in this description, the frame from which the outcomes are evaluated is immaterial. The important aspect is the relative value of the outcomes. Here, a 'very good' outcome is universally preferred to a 'moderately good' outcome, which is universally preferred to a 'moderately

poor' outcome, which is universally preferred to a 'very poor' outcome.

5 For example, if one player cheats and the other cooperates, the cheater receives 12 and the cooperator receives zero. If both cooperate, both receive 10. If both cheat, both receive 2.

6 In addition to all the points between genes, most GAs also allow for the random selection of the crossover to return the point before the first gene or the point after the last gene. When this occurs, the child chromosome effectively has only one parent.

7 This example is inspired by the works of Robert Axelrod, Michael Macy, and John Miller.

8 As with all the sub-mechanisms being described, there are many different ways to implement mutation. When the number possible values of a gene is greater than two, mutation is often implemented as a random draw across all possible values of the mutation gene.

9 Here, sampling with replacement implies that one agent can be selected as the parent multiple times.

10 For an example of a black-box implementation of a GA in strategy research, see Fisch (2003).

11 This is not to imply that the GA approach does not embody local search. As discussed below, local search is one of the motivations for the use of the mutation operator. Nor should these statements imply that the models introduced by Nelson and Winter (1982) ignore imitation. Rather, this is a commentary on the relative emphasis across these two approaches.

12 According to Angwin (2009: 9), MySpace was the most trafficked website in America, in terms of pages viewed, in June 2008. Angwin notes that Google had more unique visitors, but that Google's visitors did not view as many pages.

13 Social networking sites allow users to display photos and information on a personal homepage. Users identify other users as 'friends', who are allowed to view their homepage.

14 Source: www.comscore.com, queried 2008, author's own calculations.

15 Angwin (2009: 60).

16 In a typical GA, the probability that the child chromosome draws evenly from all parents is quite low. Often, the majority of the chromosome comes from one parent.

17 As Nachbar (1992) notes, if Axelrod's agents only have three periods of memory, they will be unable to tell that the game had a fixed length of 151 iterations. At best, such agents could learn that there was a 1/148 chance the game will end any time after the first three iterations. The agents in Axelrod's study were actually playing an indefinite IPD game, for which mutual adoption of the Tit-for-Tat strategy and the associated 'always cooperation' is well known NE.

18 Dawid (1999: 111).

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14

Organizing at the Edge of Chaos: Insights from Action Research

Donald MacLean and Robert MacIntosh

INTRODUCTION AND OVERVIEW

In this chapter we explore links between complexity theory and action research in the context of research conducted within organizations. Researchers who choose to study organizational settings often do so with the aspiration of producing knowledge that would allow members of those organizations, and in particular managers, to work more effectively together (Beech et al., 2010). This concern is linked to the so-called 'relevance debate' since some argue that organizational research should be useful to those charged with running organizations (see Starkey and Madan, 2001; Starkey et al., 2009). Eminent scholars have repeatedly commented that much of the management research appearing in top-rated academic journals is of little relevance to most practitioners (see Smith and Robey, 1973; Schein, 1987; Gopinath and Hoffman, 1995; Kelemen and Bansal, 2002).

Action Research has a long tradition in the social sciences but does not feature regularly in most major international journals; one analysis showed that action research appeared only sporadically and that the majority of published articles were either discussions of the merits of the method itself or calls for greater use of the method (MacIntosh and Wilson, 2003). In general terms, qualitative research is sometimes styled as the poor cousin of 'real science' and something which is best kept in 'the closet' (Sutton, 1997). If this is the case, action research is the poor cousin's downtrodden neighbour (MacIntosh and Bonnet, 2007: 321).

We argue that there are obvious parallels between action research and complexity thinking. When conducting Action Research in an organizational setting, both the action and the research take place in real time. Both are affected by a large number of unforeseen variables. Seemingly small themes in both can come to dominate the process.

For us therefore, the potential implications of complexity theory for action researchers follow from turning complexity thinking towards the conduct of research itself. All management research, but perhaps in particular Action Research, might be seen as a complex and unpredictable dynamic whose practices, processes and outcomes emerge from the conduct of the research as it proceeds and which can neither be specified in advance nor controlled to any great degree.

The need to embrace the concepts of emergence and self-organization in both the content of the research and the process of conducting the research tends to preclude research designs which are fully specified at the outset. This chapter also discusses significant differences in the way the role of the researcher is conceptualized.

COMPLEXITY AND CHANGE

The nature of organizational change is perhaps one of the most heavily researched topics in the field of management. A number of researchers adopt a punctuated equilibrium model of change which describes periods of relative stasis, periodically interrupted by episodes of rapid and often radical change (e.g. Abernathy and Utterback, 1978; Miller and Friesen, 1984; Tushman and Anderson, 1986; Van de Ven, 1987; Gersick, 1991; Anjali Sastry, 1997). In some cases these punctuations are equated with changes from one organizational archetype to another (e.g. Greenwood and Hinings, 1993). Brown and Eisenhardt argued that whilst this punctuated equilibrium model was 'in the foreground of academic interest' (1997: 1) it was not the experience of many of the firms that they encountered.

A counter view exists in the literature, offering a description of change as continuous or incremental process (see Burgleman, 1991; D'Aveni, 1994; Brown and Eisenhardt, 1997; Chakravarthy, 1997). Increased interest in change as a continuous process may be linked to the emergence of highly turbulent operating environments across a range of industrial markets and not-for-profit sectors.

Weick (1979: 215) pointed to the need for organizations to display a mix of flexibility and stability and Chia (1999: 210) has called for alternative conceptualizations of change processes which take into account 'the inherent dynamic complexities and intrinsic indeterminacy of organizational transformation processes'. Leana and Barry (2000) have also attempted to move beyond the simple dichotomization of change as either continuous or discontinuous, to investigate stability and change as the simultaneous experiences which in many ways define organizational life. Huy (2002) has considered the issues of change and continuity at the level of the individual, whilst Eisenhardt (2000: 703) has argued that these 'co-existing tensions create an edge of chaos, not a bland halfway point between one extreme and the other'.

The term 'edge of chaos' was first coined in the natural sciences and has since been adopted by some management researchers seeking to apply complexity theory to the issue of organizational change (e.g. Anderson, 1999; Pascale, 1999). Organizations 'on the edge of chaos' are attributed with the ability to exhibit spontaneous, prolific, complex and continuous change (Kelly, 1994; Kauffman, 1995).

In this chapter, we offer both a theoretical and an empirical action research investigation of the 'edge of chaos' concept in organizational settings based on a five-year study conducted within a network of 18 organizations drawn from the public and private sectors in the UK. The study examined how common the 'edge of chaos' experience was in a range of different organizational settings, and what (if any) managerial and organizational practices were involved in operating on the edge of chaos.

We concur with Cohen's view (1999: 375) that 'we do not yet have a unified, theoretically coherent account of complexity'. Yet, as Anderson has remarked (1999: 217), management scholars have 'passed the point where a summary of these ideas … or an assertion that an empirical phenomenon is consistent with them' adds much value. Taking these observations on-board, we probe beyond the descriptive metaphor of organizations operating at the edge of chaos to seek empirical evidence of the managerial practices that characterize this state of affairs.

Using data from our study we developed two key constructs. First, in the two organizations which did appear to operate on the edge of chaos, managerial practices such as acquisitions and hiring new staff (Marcus and Nichols, 1999) are combined with less palatable processes of manipulating people and events, as well as deliberately circulating mis-information. We characterize these practices as 'managing on the edge of something'. Second, we found two other cases where explicit attempts were made to position organizations on the edge of chaos. The managers concerned in each case enacted practices which theorists recommend in order to produce edge of chaos behaviours, such as increasing participation in decision making (Ashmos et al., 2002) and attempting to encourage self-organizing processes (Pascale, 1999; Stacey, 2003). We characterize these management teams as 'the new Romantics'. Our conclusion is that organizations can operate on the edge of chaos, but that much of the advice offered in the literature to date is misleading, self-contradictory, ineffective and counter-productive. This might be related to the failure of extant research in complexity and management to develop the understanding of context and practice that can result from rigorous action research.

COMPLEXITY AND THE EDGE OF CHAOS

An in-depth description of complexity theory and its origins would be inappropriate here; interested readers can find such descriptions elsewhere in this book or in other sources (we recommend Waldrop (1992) or Coveney and Highfield (1995)). Justifications of the use of complexity theory to study organizations (McKelvey, 1997; Matthews et al., 1999) and why it might be important to managers (Anderson, 1999; Lewin, 1999) also exist elsewhere. A brief introduction to the concepts used in the remainder of the chapter is, however, warranted.

The field of complexity theory offers two views of change processes, the edge of chaos view and a dissipative structures view. Organizational applications of these concepts mirror the pattern that has occurred in the natural sciences, in that usage of the dissipative structures view pre-dates its edge of chaos counterpart (see Gemmill and Smith, 1985). Dissipative structures have been used to describe regional development (Allen, 1997), organizational change (Gemmill and Smith, 1985; Leifer, 1989; MacIntosh and MacLean, 1999) as well as individual change (Gersick, 1991). The original research on dissipative structures was conducted in the fields of physics and physical chemistry (Jantsch, 1980; Prigogine and Stengers, 1984) and describes qualitative, systems-wide changes which occur episodically, in distinct phase transitions initiated by some external trigger. During these phase transitions, the system concerned imports energy and exports entropy (a measure of disorder). Whilst in this highly unstable state the system becomes susceptible to tiny signals and random perturbations that would have had little impact were it still at equilibrium. Processes of positive feedback can turn these tiny changes into 'gigantic structure breaking waves' (Prigogine and Stengers, 1984: xvii). Since dissipative structures consume energy, they tend to stabilize again and return to equilibrium if, or when, the supply of energy stops. However, neither of these views made a clear distinction between change in the sense of a reconfiguration of existing elements, and real qualitative change where new types of element, with new behaviours or characteristics, emerge or invade the system (Allen, 1976: 2006).

Subsequent research in the field of biology (see Kauffman, 1993; Solé et al., 1993) adopted a different perspective claiming that, rather than experiencing periodic punctuations, systems can exist in a zone on the edge of chaos. The edge of chaos perspective is most frequently associated with work in so-called living systems (e.g. insect colonies, organisms, the human body, neural networks, etc.). Goodwin (1994: 169) claims that 'complex, non-linear dynamic systems with rich networks of interacting elements (have a zone which) … lies between a region of chaotic behavior and one that is frozen, with little spontaneous activity'. Systems on the edge of chaos appear constantly to adapt, self-organizing again and again to create configurations that ensure compatibility with the ever-changing environment. This perpetual fluidity is regarded as the norm in systems on the edge of chaos, as opposed to a periodic feature of systems that undergo dissipative transformations from one stable state to another. Again these two views do not really consider change and adaptation as arising from the appearance of elements with novel behaviours and characteristics.

It has been noted that 'the edge of chaos is a good place to be in a constantly changing world because from there you can always explore the patterns of order that are available and try them out … you should avoid becoming stuck in one state of order which is bound to become obsolete sooner or later'. (Brian Goodwin quoted in Coveney and Highfield, 1995: 273).

The concept of an organizational edge of chaos has been widely adopted with proponents claiming that the level of innovation and creativity it confers on organizations may offer a source of competitive advantage (Brown and Eisenhardt, 1998). Such organizations are said to 'transcend fixed structures and centralized control; they are systems or processes that produce a constant stream of structural change throughout the organization' (Halal, 1993: 40). The visibility of early work at the Santa Fe Institute and the broad popular appeal of associated books on the new science (e.g. Waldrop, 1992; Wheatley, 1992) saw the 'edge of chaos' develop into something of a saleable brand during the 1990s. Populist managerial texts offered advice on 'living on the edge' (Youngblood and Renesch, 1997) and 'leading at the edge' (Conner, 1998), whilst management consultants used the concept in relation to organizational strategy (see Beinhocker, 1997).

Despite this popularity however, Pascale (1999: 85) notes that 'one cannot direct a living system, only disturb it'. Furthermore, Stacey's extensive work in this area (1991, 1995, 2003) centres on the assertion that we cannot accurately predict (or control) what happens in the future. For those adopting this view of organizations, the roots of unmanageability can be found in the fact that systems on the edge of chaos are both extremely sensitive to initial conditions and highly nonlinear in evolutionary terms. A number of authors argue that acknowledgement of this fact should be central to the quest to develop new ways of 'managing' our organizations (e.g. Shaw, 1997; Stacey, 2001; Streatfield, 2001).

One of the critical issues in developing new ways of managing is 'to figure out what to structure, and, as essential, what not to structure' (Brown and Eisenhardt, 1998: 12). Maguire and McKelvey (1999: 31) point out that 'the edge of chaos is not something which is necessarily there that managers have to contend with … it is a region that they create, consciously or inadvertently'. In the light of these observations, and in the face of the 'tenuous connection between cause and effect' (Pascale, 1999: 92), the action research discussed in this chapter sought to discover and understand what managers could, and should do by actually working with them in change initiatives informed by complexity theory ideas.

RESEARCH SETTING

The study involved 18 organizations from the public and private sectors in the UK. Some of the larger multi-national organizations were not UK-based; in these cases research was conducted with UK-based subsidiaries or production facilities. Each organization was keen to explore the managerial implications of complexity theory (see MacLean and MacIntosh (2002) for a more detailed account of the study). Senior managers from each organization in the study met every six to eight weeks over a five-year period. Organizations in the study were sub-divided into three categories: large private sector firms, small to medium sized enterprises (with under 250 employees, described as SMEs from this point) and public sector organizations (see Table 14.1).

METHODS

We felt that our study should adopt research methods which were consistent with the theoretical basis of our enquiry. The key question we faced was how to view our own involvement, if the research process itself was a complex adaptive system subject to phenomena such as non-linearity, disequilibrium, emergence, etc. Complexity theory indicates that small disturbances can be amplified into system-wide effects in unpredictable ways. Despite backgrounds (and PhDs) in engineering and physics, this led us as researchers, away from a view of ourselves as detached, unobtrusive observers and towards a role as creative participants in an unfolding (and essentially unpredictable) dynamic.

In the terminology of traditional research, we followed a research design akin to the multiple case method used by Brown and Eisenhardt (1997) and which had been developed from Yin's work on case study research (1984). The organizations in the network were treated independently and a narrative account (Tsoukas and Hatch, 2001) was prepared for each describing the most recent (or in some cases, on-going) organizational change experience(s). These accounts were shared within the network of organizations participating in the study (subject to the use of confidentiality agreements to deal with any commercial or other sensitivities).

To help move beyond superficial usage of the edge of chaos metaphor, we augmented this style of research with a more highly-engaged, form of research which was more cognizant of complexity thinking. In part, this decision was influenced by Boje's observation that context is essential for interpreting narratives that occur in organizational settings and that without participating in the organization that contextualizes a narrative, meaning is difficult if not impossible to grasp (Boje, 1991), i.e. meaning (the meaningfulness of research) is itself an emergent complex and participative dynamic.

We felt that using action research as a starting point would allow us to gain meaningful access to the unfolding dynamic of a social system in a way that was necessary if we were to gain appreciation of the subtleties and nuances which might be important to our understanding and theory-building. Concerns about the extent to which our objectivity might be compromised by such a high-engagement form of research were allayed partly by the use of mixed methods (including more traditional case study research as indicated above). As a result, we developed a richer understanding of the concept of emergent properties in research. From such a perspective, involvement is not cast as some distorting influence on objectivity but as the creative engine of the production of knowledge and shared meaning.

Action research (as pioneered by Lewin, 1947) has a long history in the field of

Table 14.1 Organizations in the study (anonymized)

Large private sector firms	*SMEs*	*Public sector organizations*
Drinks Co	Baker A*	UK Univ 1*
Power Up	Engineer Co*	Health Org B*
Brand Co	Build It Ltd	Media Comm
Pharma 1	Martin Bells Ltd	Local AuthoriT E
Electronix A*	DPN Services	Economic Dev.
CommuniCo*	Smith & Assoc.	Environ Plus*

* *Conducted extended action research projects with these organizations.*

management (see Reason and Bradbury, 2001) yet Eden and Huxham (1996: 78) report that action oriented approaches can experience difficulty in finding acceptance on the grounds that they are not science. Proponents of such research argue that this is because such action-oriented research must be viewed and evaluated differently than traditional science (see Susman and Evered, 1978). A more detailed exposition of our methodological stance for mode 2 management research is available elsewhere (see MacLean et al., 2002).

In seven of the 18 organizations, we conducted longer-term, action research studies ranging in duration from 8 to 20 months. Through the creation of the narrative accounts for all 18 organizations in the study, it became apparent that three types of change experience might be studied. The first type involved a stated intention to move from one relatively stable state to another. The second type would involve those organizations that already appeared to be operating in a manner consistent with the edge of chaos descriptors. The third, and perhaps the most interesting category in managerial terms, would involve those organizations that intended to switch from a stable state to a position on the edge of chaos. Given that the success or failure of these change processes could not be known in advance, we elected to establish a range of studies.

Our direct involvement in action research within seven organizations from the study, afforded us the opportunity to collect primary and secondary data, attend key management meetings, contribute opinions and suggestions, conduct interviews and hold both on-site and off-site workshops and reflection session with staff from the organization.

THEORETICAL INSIGHTS

Our first theoretically informed insight related to an inherent contradiction in some researchers usage of the edge of chaos concept. As we have already highlighted, those adopting the edge of chaos concept often point to the 'unmanageability' of systems in this state (e.g. Stacey, 2001; Streatfield, 2001). There appears to be an inherent contradiction between the observation that you cannot manage, direct or control systems on the edge of chaos and the normative suggestion of more populist writers that managers should attempt to manoeuvre their organizations into just this state. There are varying degrees of willingness to accept some level of managerial control or influence with some authors (e.g. Stacey, 2001) pointing to the fallacy of attempting to manage the unmanageable, whilst Brown and Eisenhardt (1998) offer prescriptive advice on five building blocks for competing on the edge. The subtle distinction between creating edge of chaos conditions in an organization and managing its behaviour once positioned at the edge of chaos also appears to be overlooked in the literature.

If this seems problematic, our second theoretically informed observation is potentially even more damaging to the edge of chaos concept. The edge of chaos concept first arose in the natural sciences when researchers at the Santa Fe Institute and the University of Illinois equated computational ability with the ability to adapt and survive, using cellular automata to explore their hypothesis that such ability became infinite in a regime which was between periodic and chaotic behaviour (reported in Coveney and Highfield, 1995: 273–277).

Separate empirical and theoretical work on ant colonies suggested that real colonies exhibit an organizational structure which in terms of spatial density corresponds to a transition between order and chaos, allowing the ants to behave as a 'superorganism' (Gordon et al., 1992). Yet prior work at Berkeley and subsequent work at Santa Fe suggests that whilst computational ability appears to increase in the transition zone between order and chaos, it does so at the onset of chaos (i.e. in the chaotic regime). There thus appears to be a case for arguing that order emerges 'out of chaos' (Prigogine and Stengers, 1984) rather than on the 'edge of chaos'. This argument appears to be gaining broad acceptance, with some of the claims concerning the edge of chaos being attributed to different usage of the term chaos (which of course, is a well defined mathematical term describing a state which is intermediate between order and randomness in nonlinear dynamical systems). The lack of clarity surrounding the edge of chaos concept is further compounded by vagueness in relation to the definition of the 'edge' in question, and which dimension(s) of the organization approach this edge, e.g. organizational structure, processes, culture, etc. (MacLean et al., 1998).

This lack of clarity may produce a false choice between the edge of chaos and the dissipative structures views of organizational change. If the organization is considered to exist in both physical and cognitive terms (e.g. as a set of physical structures and as a set of mental models, routines, etc.), then it could be that only one of these dimensions is subject to on-going, incremental change processes.

Finally, our theoretical inquiry raised concerns about the way in which the edge of chaos concept is being translated from the natural sciences to social science settings. Much of the original research which led to the edge of chaos concept involved either the study of computer models (e.g. Kauffman, 1995) or animal behaviour (e.g. Gordon et al., 1992). The translation of findings from these settings to the social sciences obviously introduces issues such as agency, but these are often glossed over managerial writings on the subject. We have argued elsewhere that, despite the fact that complexity theory itself is a new and rapidly changing field, management scholars should focus on the development of theories relating to complex adaptive social systems or CASS (see MacLean and MacIntosh, 2003) where the social dimension is embraced and made central to both the theory development and its application. Tsoukas and Hatch (2001: 981) deliberately adopt a metaphorical use of complexity as a means of expanding possibilities rather than taking a reductionist approach and searching for common laws underpinning everything.

We believe that the paucity of genuine attempts to build a social dimension into organizational applications of complexity theory is one of the primary causes of the criticism that we have not moved beyond the metaphorical. Interestingly, the only serious attempt to do so that we have found has rejected the notion of 'system' on which the whole of complexity theory is based (Stacey, 2003).

To conclude our theoretical insights, we consider the confusion that exists at the overlap between organization theory and complexity theory in terms of the relationship between stability and instability. In organization theory, we earlier highlighted the calls for a mix of flexibility and stability (Weick, 1979: 215; Brown and Eisenhardt, 1998). Yet, in complexity theory it is argued that complex adaptive systems naturally evolve to the edge of chaos (Bak, 1996) and that when positioned in this zone at the edge of chaos, systems naturally display the desired mix of flexibility and stability. Again these authors do not seem to make a clear distinction between the re-configuration of the existing elements of a system and the changes in the actual elements themselves or the nature or technology of the linkages between them. Our earlier observations about whether or not organizations can be managed towards the edge of chaos, whether such a zone exists at all and finally whether it is acceptable to treat organizational systems in the same way as ant colonies or arrays of light bulbs remain valid.

EMPIRICAL FINDINGS

The organizations included in our study were selected on the basis of the change experiences each could share with other participating organizations from the study. One of our primary research goals was to investigate how frequently edge of chaos style change processes occurred in the data and, where such behaviours were found, to characterize the managerial practices that underpinned them.

In establishing that an organization might be described as operating on the edge of chaos, we needed some criteria to make repeatable judgements across cases. The first criteria related to the duration of the change processes in the organizations concerned. In the organizations that experienced punctuated or episodic change (typically in the form of re-engineering projects, corporate restructuring or merger), the change process lasted no longer that 24 months. Given the edge of chaos pattern of on-going, incremental, self-organized change processes, we considered any change experience extending beyond this 24 month cut-off as potential examples of edge of chaos behaviour in the organization concerned. The longitudinal nature of the research process was vital in enabling us to make such judgements about each of the participating organizations.

The second criteria we developed to identify edge of chaos behaviours related to the extent to which stability was sought, desired or achieved in the change process. In many of the cases we considered, the change process was characterized by clear and distinct before and after states. Many of the change processes we studied involved preparation for and implementation of some new organizational configuration (in terms of structure, roles, responsibilities, etc.) at a particular point in time. Again, by implication we classified those organizations where this was not the case as potentially exhibiting edge of chaos behaviour.

The final criteria which emerged from our data related to self-organizing processes where order spontaneously emerges out of disorder and chaos (Toffler, 1984: xv). Management theorists have described the benefits of such self-organizing processes in organizational settings as producing structures that are fluid, yet sensitive to the needs of the elements (Ashmos et al., 2002). Hence, we looked in each of the cases for instances of spontaneous events and incidents which had nevertheless resulted in particular patterns of organizing being adopted. A succession of such self-organizing occurrences was again taken as an indicator of possible edge of chaos behaviour.

In isolation, some of these criteria occurred in all of the cases we studied. Applying this test to the 18 organizations in our study, we discovered only two instances where the change processes studied were consistent with edge of chaos type behaviours at least in terms of the criteria we had established. Detailed analysis of the circumstances, managerial practices and organizational outcomes associated with these two cases led to the development of our first key construct (as summarized in Table 14.2).

OPERATING ON THE EDGE

The change processes at Pharma 1 and Electronix A both extended beyond 24 months. The case study at Pharma 1, the older of the two organizations, revealed a history of continuous change traceable over a 15 year period whereas according to the CEO of Electronix A 'the organization had been in a state of flux over its short 3 year history'. Both Pharma 1 and Electronix A appeared to be operating on the edge of chaos, had been doing so before our study began, whilst continuing to do so during the study.

Understandably, this meant that neither case highlighted distinct transitions from one discernible state to another. More interestingly however, both organizations claimed that this was a deliberate ploy. The most senior operational manager at Pharma 1 was described by staff as 'a bit like a chess player, making changes, reviewing the pattern, keeping things interesting'.

This emphasis on continual change had led each organization to a propensity for resolving problems through self-organization. Those closest to the problem would often resolve issues through direct communication

Table 14.2 Key constructs

Organizations	*Managerial practices*	*Organizational outcomes*	*Key construct*
Electronix A and Pharma 1	*Acquiring new businesses* – to maintain a sense of fluidity *Staff rotation* – to avoid individuals building empires *Manipulation of both events and individuals* – to maintain a sense of uncertainty *Peddling rumours and untruths* – to induce a sense of anxiety	Produced a state of perpetual uncertainty and anxiety amongst staff. Staff seemed more likely to engage in self-organizing behaviour to address problems.	Managing on the edge of something
Environ Plus and Engineer Co.	*Move to new sites* – to provide a symbolic break with the past *Introduce new Structures* – to produce new forms of collaboration within the organization *Increase participation* – to engage the whole organization in key decisions *Develop new Skills* – often in the form of multiskilling, etc.	Produced a sense of scepticism about the changes. Staff expressed concerns that old power structures were still in operation despite repeated assurances in the early stages. Management become frustrated *but* when subsequently faced with crisis situations, the management acted in ways which confirmed staff suspicions.	The New Romantics

with key players, but without recourse to higher levels of management. The CEO of Electronix A commented on several localized examples (re-organizing shift patterns, re-designing products and production processes, etc.) which had just 'happened'.

In what might already be considered a somewhat biased sample of 18 organizations with prior knowledge of the edge of chaos concept, the low frequency of its occurrence does run counter to Brown and Eisenhardt's assertion (1997: 1) that many firms compete by changing continuously. Both organizations were, however, in knowledge-intensive, high technology industries (pharmaceuticals and electronics) and each organization did operate with shortening product life cycles and rapidly shifting competitive landscapes (Brown and Eisenhardt, 1997: 1).

The most striking feature of the two edge of chaos cases related not to the strategic behaviours that it produced but to the managerial practices which appeared to be required to manoeuvre the organization to the edge of chaos and maintain its position there. In both cases, the management practices employed indicated that organizations do not naturally migrate to the edge of chaos. Both Electronix A and Pharma 1 exhibited semi-structures (Brown and Eisenhardt, 1997) but these semi-structures were produced by the deliberate destabilizing activities of the managers concerned. This is consistent with complexity theory in the natural sciences where it is argued that a continuous supply of energy is required to maintain the change process, but inconsistent with views that organizations were essentially unmanageable.

At any given point in time Pharma 1 and Electronix A were expected to be operating with a single structure but the pace of change was deliberately set at a level above that with which the organizations could cope. For example, Pharma 1 had adopted an aggressive growth strategy fuelled by regular acquisitions (as many as 15 in a single year).

As each acquisition occurred a new set of structural arrangements would be drawn up dealing with both internal organization and the servicing of external markets. These plans rarely had the chance to become embedded as some subsequent acquisition was in progress before this could happen. In parallel with this practice, both Pharma 1 and Electronix A used job rotation and restructuring to maintain a level of instability that was viewed as crucial in delivering edge of chaos type behaviour. The CEO at Electronix A described these strategies as 'a way of maintaining uncertainty and the feel of a start up situation long after most other organizations would have settled down into a particular mode of operating'.

Another key conceptual contribution from Brown and Eisenhardt's study of high velocity industries related to what they describe as 'links in time, practices that address the past, present and future … and transitions between them' (1997: 29). In both Electronix A and Pharma 1, such links in time were not dealt with by the organization in a collective manner. Rather, the linkages between the past, present and future were the exclusive preserve of a single figure at the top of the organization. The description given earlier of the chess player captures the nature of this role, but it was also described by the two individuals concerned as 'a lonely role, having perpetually to keep everyone on their toes … even to the extent that you deliberately peddle untruths and misinformation to keep things from settling into a rhythm'.

These two organizations where edge of chaos behaviours were observed were characterized by managerial practices which ensured a degree of physical instability (in terms of structures, roles, etc.). Both cases also featured practices designed to produce cognitive instability (through the use of conflicting information, rumours and misinformation). These latter practices could be considered unethical (Darley et al., 2001) and hence we have described Pharma 1 and Electronix A as operating at 'the edge of something' – the 'something' could as easily been read as being the edge of ethics as the edge of chaos.

THE NEW ROMANTICS

In two of the other extended action research studies, organizations initiated change processes with an explicit desire to produce organizational behaviours consistent with the literature's description of the edge of chaos. These attempts to develop edge of chaos behaviours were unsuccessful both in terms of the three criteria set out in our diagnostic test set out earlier, and in the opinion of staff from the organizations concerned. A detailed review of these cases led to the development of our second key construct, which we termed 'the new Romantics', since we were struck by parallels with the way in which the Romantic Movement (*c.* 1750 to *c.* 1900) cherished intuition, emotion, inspiration and creativity, in part as a revolt against the Renaissance's preference for orderliness and logical methods of thought and design.

Environ Plus was a newly formed public sector organization created through the amalgamation of 63 smaller, independent, regionally based organizations covering a range of related activities. The formation of a new, national organization was accompanied by significant efforts on the part of senior management team to develop a new, innovative, flexible culture in what had been traditional and somewhat staid sector. High levels of physical instability were present in Environ Plus as new offices and a new location were chosen, roles changed, new processes were put in place, etc. Over time, the organization displayed surprisingly little cognitive instability and the various different professional groups slowly began to reassert both their power bases and their traditional ways of working. After a brief flirtation with the edge of chaos, Environ Plus reverted to a more stable pattern of behaviour and subsequent organizational changes were more consistent with the dissipative structures model.

Over the same period, Engineer Co also attempted to adopt edge of chaos behaviours. The company, a traditional mechanical engineering factory formed in the nineteenth century was under increasing pressure to improve performance in financial terms or run the risk of disposal and possible closure. The managing director who participated in the study recognized 'the need for wholesale change and an enduring sense of 'changefulness'. The company had been organized along functional and hierarchical lines for as long as anyone could remember – with a 'do as you're told' mentality pervading the organization. The kinds of performance improvements required to make Engineer Co competitive (e.g. significant lead-time reductions and new rapid and radical product development), were unlikely to be realized unless a more dynamic, team-based, networked organizational form could be introduced. The espoused characteristics of an organization operating on the edge of chaos appealed greatly to the management team at Engineer Co.

In the action research we undertook, extensive work with the senior management team did seem to produce genuine changes in its behaviour. However, over a period of 18 months, these changes appeared to be restricted to the management team and the remainder of the organization continued to resist efforts to encourage wider participation in the change process. A completely new structure based around business units was introduced but despite the best efforts of the management team there were very few instances of self-organized, spontaneous or non-directed change. Eventually, the managing director who had instigated the change programme admitted that Engineer Co could not be described as operating at the edge of chaos despite strenuous efforts to make this happen.

Ashmos et al. (2002: 190) argue the case for making organizations more internally complex by encouraging participative decision-making. Senior management at both Environ Plus and Engineer Co did attempt to introduce greater levels of participation in an effort to produce edge of chaos type behaviours in the organizations concerned. In both cases, this participative approach failed and any changes that the organizations did experience were more accurately described as punctuated or episodic. In the case of Environ Plus these attempts met with early success but later crises were eventually dealt with in an authoritarian fashion reminiscent of the predecessor organizations which had formed the basis for Environ Plus. In the case of Engineer Co, those outwith the management team never overcame their scepticism at attempts to involve them in decision making processes.

Of course, this may simply signal a managerial failure to operationalize the edge of chaos concept. We would argue however, that a more compelling explanation lies in the existence of a fundamental inconsistency between edge of chaos behaviour and the deliberate practices of progressive managers emphasizing the importance of widespread participation in organizational design and strategy making.

The other remaining 14 organizations in our study exhibited change processes which were consistent with a dissipative structures description (see Table 14.3a–c). These change processes were characterized by clear, stable before and after states which were separated by a short period of instability. In these cases, rather than naturally remaining poised on the edge of chaos, the organizations reverted to a stable format (either the old archetype or some new replacement – see MacIntosh and MacLean (1999) for a fuller account of such behaviours). Many of these 14 organizations embarked on change processes as a response to some external stimuli. Baker A faced financial ruin when the slow erosion of their traditional markets was exacerbated by a national food safety scare relating to beef. Meat products represented 40% of Baker A's output and the market for these products collapsed in a matter of weeks. Drinks Co. was a successful international company which embarked on a change

Table 14.3 Overview of Data Set

Organization	*Description of change process*	*Driver(s)*
(a) Large Private Sector Firms		
Drinks Co	Drinks Co was a large, multinational firm operating in mature markets. Slow growth in the sector led to a merger with another similar sized competitor. The change process studied involved the planning and implementation of a new approach to manufacturing and distribution. Two sets of manufacturing plant and distribution channels were consolidated into a single operation. A BPR project was undertaken which spanned a 12-month period, after which the new processes 'went live'. These new processes took products from 64 production lines at 4 different production sites and distributed them to over 200 markets world-wide.	Externally triggered by demands for improved shareholder value, the merger was presented to the stock market as a way of achieving significant cost reductions and doubling shareholder value within a 4 year period.
Power Up	Power Up was formerly a publicly owned utility, providing a single service to a single domestic market. Following privatization and deregulation, Power Up sought to achieve rapid improvements in performance levels and to expand. This led to the acquisition of new businesses as Power Up sought to move from being a single utility to being a multi-utility organization offering gas, electricity, water and telecommunications services. The change process studies here related to the HR function of Power Up as it sought to co-ordinate training, development, remuneration, etc. across the newly acquired businesses.	The initial triggers were legislative changes which first privatized a range of different public utilities over a period of time, then allowed ownership of more than one utility type by a single organization.
Brand Co	A highly successful firm which developed and produced a diverse range of household products, Brand Co. undertook a major re-engineering project to improve the performance of its product development process. The re-engineering project involved key players from a range of organizational units which serviced a diverse range of markets.	Alongside the objectives of reducing costs and lead times, a major driver for the project was the search for synergies between the vast range of markets and products which Brand Co managed.
Pharma 1	Pharma 1 offers a range of services to the pharmaceuticals industry and has experienced rapid growth as a result of the trend toward outsourcing of non-core activities in the sector. The change process studied was the rapid growth of the firm as it aimed to achieve $1 billion turnover through an aggressive pattern of acquisitions and developing new markets and services. High levels of growth were being achieved through an acquisition rate of between 10 and 14 new businesses each year.	The change process appeared to be internally driven by the desire to achieve a particular target which had been a feature of the organization for some time.
Electronix A	Electronix A supply a variety of components for use in a range of electronic devices. This US based organization was establishing a manufacturing plant to service the European mobile phone industry. The change process being studied here was the establishment of a new manufacturing facility over a period of 36 months.	Whilst the initial trigger for change was external (i.e. the decision by the parent company to establish a new site), on-going changes once the plant was opened were driven internally.
CommuniCo	This study took place within the UK division of a global IT services organization which employed over 100,000 staff world-wide and had an annual turnover of $15 billion. Several years of rapid expansion had come to an end, and as the business stabilized there was increasing pressure to reduce costs in order to maintain the kind of margins that shareholders had come to expect. The change process studied related to the development of new ways of delivering a key service contract. The new contract was to be arranged on a rolling basis, valid for 3 years but revisited every year.	The driver for this change process was a corporate plan to improve productivity and profitability. This was generated by 'head-office' and was being operationalized by the various divisions.

(b) Small to Medium Sized Private Sector Firms

Baker A	A family owned firm, Baker A had operated successfully for the majority of its 80 year history. However, recent trends in the market had led to a decline in sales as customers began to shop at large supermarkets (which Baker A did not supply) instead of small local shops (which were Baker A's primary distribution channel). The organization recorded a substantial financial loss for the first time and this instigated a change programme to reduce costs, introduce new products and penetrate new markets. This change process occurred over an 18 month period.	The gradual changes in consumer behaviour were accentuated by the BSE crisis in the UK. This had the effect of decimating demand for meat-based products which, at the time, represented 40% of turnover.
Engineer Co	A UK based subsidiary of a US engineering firm, Engineer Co manufactured complex products for the energy industry. Originally an independent company founded in the nineteenth century, Engineer Co was now under increasing pressure from its US parent to improve performance in financial terms or run the risk of disposal and possible closure. A new MD was appointed and he instigated a 24 month change programme aimed at restructuring the business and restoring profitability.	Trading difficulties had been exacerbated by exchange rates which effected the firm's competitiveness in export markets. The key trigger was however, the appointment of a new MD.
Build It Ltd	This firm offered sub-contracting services to large construction companies in markets as diverse as road building and domestic housing. The firm employed over 340 staff, many of whom had worked for Build It for over 20 years. The charismatic MD who had presided over a period of massive expansion now wanted to step down from his post and oversee the development of other new businesses which had been acquired. This change process involved the board of directors (who were technically rather than commercially trained) developing new skills and working together in new ways.	The acquisition of two new businesses, both of which required management attention, triggered the changes envisaged at top level in Build It.
Martin Bells Ltd	A family owned firm which manufactures and distributes specialized components for use in the process industries. Martin Bells was operating successfully despite the appearance of large multi-national competitors in many of its key markets. The change process studies here involved changes in the senior management team as the existing MD (and co-founder of the business) handed over control to his son.	The trigger for change in this instance was the announcement by the existing MD that he wished to retire from the business, whilst still retaining a significant shareholding.
DPN Services	DPN offered consultancy services to the construction industry. The change process studied here involved the development of a new product/service based around the electronic capturing and management of building details via a new piece of software. In a traditional and highly paper-intensive sector, this innovation appeared to be changing the very nature of DPN's business.	An unforeseen development which evolved from one person's attempts to improve their own data management and become a whole new area of business activity.
Smith & Assoc.	Smith & Assoc. started as a professional partnership and became a limited company as the senior partner attempted to ensure that everyone held some equity in the firm. The firm faced a series of changes culminating in the incumbent MD announcing that he no longer wanted to fulfil this role. The firm then faced a period of introspection as a new MD was sought and appointed.	Again, the trigger for change here was the announcement by the current MD that he wished to step down, but remain working for the firm.

(*continued*)

Table 14.3 Overview of Data Set (*cont.*)

(c) Public Sector Organizations

UK Univ 1	The change process here related to the University's approach to managing student records. The existing system was cumbersome, distributed and duplicated. A BPR project was initiated to move all parts of the University to the use of a single, centrally held, electronic record. UK Univ 1 employs over 5000 staff and a small team of 35 people was formed to undertake the process. The project has been running for over 4 years.	Increased pressure on resources led to a drive for improved efficiency. These pressures proved an indirect trigger for the change process at UK Univ. 1.
Health Org B	Provided a form of quality assurance service to the rest of the National Health Service in Scotland. A small core team of staff was augmented by a much larger group of reviewers and a specific range of health services were audited on a rolling basis when one member of the core staff and a team of reviewers would visit a particular site for a one week period. Health Org B felt the need to transform the way it operated in light of the changes in its operating environment. This process extended over 12 months.	A number of triggers included changes in the political system (as a new Scottish parliament was established) and the fact that a new health inspectorate was set up covering a far broader range of health services.
Media Comm	A publicly funded broadcaster faced a period of unprecedented upheaval as both the marketplace and broadcasting technology changed. The change process studied here related to Media Comm's HR policies as they began to outsource more of their production services.	A drive by the government to ensure value for money for publicly funded services translated into specific initiatives within Media Comm.
Local AuthoriT E	The change process studied here related to the introduction of new working practices in the Social Work department. These new practices involved multi-skilling, the use of flexi-time, etc. The change process took place over a period of 6 months and was characterized by a long period of planning followed by a short implementation phase.	The driver for this change was a desire to improve the responsiveness of the particular service concerned. The changes were not made in response to any specific external signal.
Economic Dev.	One particular department of a national, government funded economic development agency was asked to participate in a 'workplace of the future' project. The project involved moving to new offices which would feature extensive use of mobile computing and telecommunications technology, hot-desking, remote working, etc. The project ran for an 18 month period but was preceded by a 6 month consultation, planning and preparation phase.	The trigger for change here was the opportunity to participate in a funded demonstration project.
Enviro Plus	Enviro Plus is a national agency responsible for policing a range of environmental protection legislation. The formation of Enviro Plus involved the merging of a large number of smaller, regionally based organizations and the change process studied here ran over a period of 36 months.	The driver for change in this instance was the introduction of new legislation which necessitated the creation of a new national agency.

process following the announcement that it was to merge with a rival organization.

DISCUSSION

This chapter describes the use of action research, in combination with traditional case study research, to explore the application of complexity theory in organizations. Specifically, the study described here sought to discover how common the edge of chaos experience was in a range of different organizational settings, and what (if any) managerial and organizational practices were involved in producing these behaviours.

In describing our theoretical insights, we pointed out that some researchers in the natural sciences have questioned the validity of the very concept of the edge of chaos. Mitchell has argued that, 'to the extent that one can make sense of what (was) … meant by the "edge of chaos", (the) … interpretations are neither adequately supported nor are they correct on mathematical grounds' (quoted in Coveney and Highfield, 1995: 276).

Despite these criticisms, our research would seem to indicate that some organizations can operate whilst positioned somewhere between a stable, structured state and one of total randomness. Despite arguments that 'change is the normal condition of organizational life' (Tsoukas and Chia, 2002: 567), our study indicates that this is not the natural, or default, state for organizations. Rather, we would concur with Brown and Eisenhardt's contention that maintaining a position on the edge of chaos, where change is continuous, represents a serious challenge because such a position is a dissipative equilibrium and requires constant management vigilance to avoid slipping into pure chaos or pure structure (1997: 29). Since only two of the 18 organizations studied displayed these edge of chaos behaviours, we would argue that the challenge of maintaining a position on the edge of chaos is one which most management teams fail to meet. Part of the explanation of this may also lie in the desire of individuals to avoid the anxiety, stress and ultimately, health problems that may accompany unremitting fluidity (Houchin and MacLean, 2005; MacIntosh et al., 2007).

Turning to the managerial practices that produce edge of chaos behaviours, we may begin to see some explanation of this. The literature offers a range of advice to those seeking to position organizations on the edge of chaos. At one extreme we find Stacey (2003), who argues that organizations are unmanageable. He criticizes the work of Brown and Eisenhardt (1998), observing that 'they make a simplistic equation between the edge of chaos and success' (Stacey, 2003: 282). Yet, Pascale argues that the edge of chaos can be attained through a precise balance between amplifying and damping feedback, and (unique to mankind), the application of mindfulness and intention (1999: 91). The former practice has also been adopted in other work on complexity theory (see MacIntosh and MacLean, 1999), whilst the latter is directly opposed to Stacey's observations about unmanageability (2003).

Pascale describes the experience of change at Shell as occurring at the edge of chaos (1999). He describes the managerial practices involved as decentralizing, encouraging the use of small teams and introducing stress through increased transparency and increased contact between senior managers and front-line staff. In our study, Environ Plus and Engineer Co introduced such practices but failed to achieve edge of chaos behaviours over the medium term. The attempts at both Environ Plus and Engineer Co to produce flexibility and adaptive capacity through greater levels of autonomy and participation did not produce the self-organizing patterns of behaviour that were anticipated.

The two organizations from our study which did achieve edge of chaos behaviours (Pharma 1 and Electronix A) also adopted these practices. In both cases, stress levels within the organizations concerned were further heightened through the use of other tactics. Explicit attempts to maintain instability focused on frequent restructuring exercises, job rotation to avoid individuals becoming comfortable in their roles and acquisitions to challenge cultures, practices, etc. These practices did produce a stressful environment but were within the bounds of acceptable managerial behaviour. We also found that in both Pharma 1 and Electronix A the most senior personnel regularly peddled mis-information, manipulated events and people to produce crises and circulated rumours about impending take-overs, loss of business, etc. These latter practices led us to describe these organizations as managing on the edge of something. Of course there is no evidence that the adoption of these practices improved the performance of the company in comparison with what would have happened if they had not been adopted. Only when companies fail can we say that whatever it was they were doing has not worked. Thus we are left with an ambiguity as to whether any changes could have saved the situation.

Conclusive judgements cannot be made on the basis of the cases presented here. We believe that a critical factor was that in both Pharma 1 and Electronix A these 'questionable' behaviours were vested in a single, powerful individual at the top of the organization.

CONCLUSIONS

In this chapter, we have established that organizations can operate on the edge of chaos in a minority of cases and we have attempted to characterize the management practices that produce these behaviours. Though not exhaustive, the five-year study of the change processes in 18 public and private sector organizations presented here indicates two key contributions – first, that edge of chaos behaviours are attainable and, second, in terms of research process, there is much to be gained by embarking on pragmatic combination of action-research and more traditional inquiry methods. This combination has yielded three key findings emerge from the work presented here. First, whilst Edge of Chaos behaviours are attainable, they are not common. Second, contrary to those who argue that such behaviours cannot be managed (Streatfield, 2001; Stacey, 2003), managerial action is central to the creation and maintenance of edge of chaos behaviours. Third, organizations operating on the edge of chaos feature high levels of stress and uncertainty for those working in the organization and these high stress levels are produced by managerial practices which we have described as being 'on the edge of something' (for the interested reader, possible links between such practices and individual/organizational health have been reported in MacIntosh et al., 2007).

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15

From Skew Distributions to Power-law Science

Pierpaolo Andriani and Bill McKelvey

At the end of the nineteenth century Vilfredo Pareto (1897) observed that the distribution of income in Italy was highly skewed and long-tailed. Pareto's observations and thinking would, over time, instigate a scientific revolution. We briefly present the main differences between traditional science and the new science stemming from Pareto's observations. Traditional (or linear) sciences are based on one of the following fundamental assumptions (West and Deering, 1995): (a) theories are and should be quantitative; (b) phenomena can by and large be represented by analytic functions; (c) systems have fundamental scales; and (d) most phenomena are additive – i.e., they satisfy the 'Principle of Superposition'.[1]

These principles are wide-ranging but not neutral. They are based on a vision of the world that embraces gradualism, linearity, reductionism and equilibrium. At various times, from Galileo to the emergence of quantum mechanics, the success of natural sciences has been so spectacular that many contemporaries held the thought that there wasn't anything major left to discover. The social sciences have been strongly influenced by the successes of natural sciences, especially neoclassical economics (Mirowski, 1989; Ormerod, 1994, 1998; Colander, 2006). Furthermore, Abbott (2001: 7) says the following about how the 'general linear model' from Newtonian mechanics came to 'shape sociologists' thinking:

> 'The phrase "general linear reality" denotes a way of thinking about how society works. This mentality arises through treating linear models as representations of the actual social world. … The social world consists of fixed entities (the units of analysis) that have attributes (the variables). These attributes interact … to create outcomes, themselves measurable as attributes of the fixed entities.'

Despite the successes of linear science, a large set of problems have proven to be intractable, such as phase transition in physics (Barabási, 2002), punctuated equilibria in biology (Kauffman, 1993), punctuations in history (Mokyr, 1998), increasing returns in economics (Arthur, 1994; Warsh, 2007), not to mention speculative bubbles and crashes in financial markets (Mandelbrot and Hudson, 2004; Cooper, 2008; Baker, 2009). These are all problems stemming from heterogeneous agents, path dependency and time-dependent connectivity among agents.

Starting from the work of Prigogine (1961), Mandelbrot (1963, 1982), Haken

(1983), Holland (1988, 1995) and many others, complexity science has dealt with the problems above by introducing the concepts of spontaneous order creation in far-from-equilibrium situations, nonlinear dynamics, self-organization and emergent properties. Nonlinear science is based on 5 basic principles (quoted from West and Deering, 1995):

1. Non-quantitative theory statements are as important, and sometimes more important, than quantitative ones.
2. Many phenomena are singular in character and cannot be represented by analytic functions.
3. The evolution of many systems, although derivable from deterministic dynamical equations, are not necessarily predictable for arbitrarily long times.
4. Phenomena do not necessarily possess a fundamental scale and can be described by scaling relations.
5. Most phenomena violate the principle of superposition (additivity).

To West and Deering's principles we add one more:

6. $N = 1$ research about extreme outcomes is often of more consequence than statistically-significant studies of large databases.

A particular subset of nonlinear phenomena exhibits the unique property of (potentially) infinite variance: the range of the dynamic behaviour of the variables is potentially unbounded. Most social, economic and organizational variables that are based on interdependency among agents tend to show this property (Andriani and McKelvey, 2009).

We argue that *Power-law Science* (PLS) constitutes the branch of complexity science that deals with phenomena characterized by high degree of heterogeneity and distributed interdependence leading to extreme variance. We claim that PLS represents a necessary, legitimate and more general paradigm than the ones that have so far dominated the social sciences. We show how the Paretian approach manages to make sense of entire classes of phenomena that are difficult or impossible to explain via Gaussian (or more generally, approaches based on finite variance), such as extreme events (West and Deering, 1995), proliferation of small niches (Anderson's *The Long Tail*, 2006), limits to knowledge, and so on.

Despite the fact that PLS is nearly a century old, the applications of PLS to Organization Science are very few and sparse. A few publications discuss the limitations of traditional approaches (Meyer et al., 2005), for instance regarding the issue of extreme events, but we know of almost no papers that discusses the contribution of PLS to organization studies – other than our own (Andriani and McKelvey, 2007, 2009, 2010), and more applied articles blogs/articles by Powell (2003), Buchanan (2004), Hagel (2007) and Zanini (2008). In this chapter we start framing the content and boundary of a new field in Organization Science.

The outline of this chapter is as follows: first we briefly discuss what a power law (PL) is and why bringing PLS into organization and management studies is essential. Then we introduce the main elements of PLS and its foundational theories. This is followed by a description of two related fields, some tools, and the use of PLs as indicators of efficacious self-organization. We close by highlighting some research challenges of organizational scientists.

INTRODUCTION TO PARETO AND POWER-LAW DISTRIBUTIONS

Defining Pareto and power-law distributions

A Pareto rank/frequency distribution plotted in terms of double-log scales appears as a PL distribution – an inverse sloping straight line; shown in Figure 15.1. PLs often take the form of rank/size expressions such as $F \sim N^{-\beta}$, where F is frequency, N is rank (the variable) and β, the exponent, is constant. In exponential

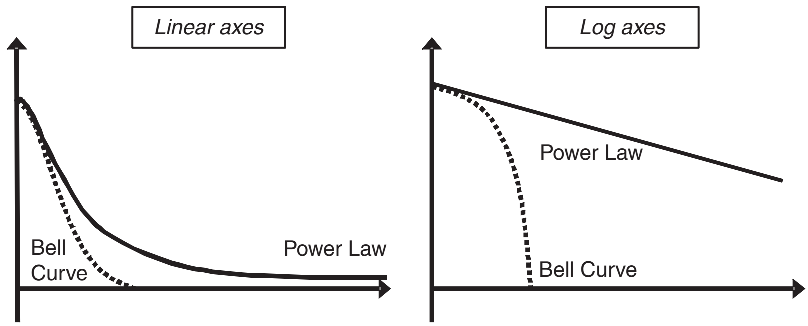

Figure 15.1 Gaussian vs Power-law distributions

functions, e.g. $f(x) \sim e^{(ax)}$, the exponent is the variable and *e* (Euler number) is constant.

Power Law phenomena constitute a subset of the larger set of nonlinear phenomena. As such, PLs share with nonlinear phenomena the typical aspects of non-additivity, openness, presence of multiple solutions and emergent properties, etc. However, what sets PL phenomena apart from nonlinear phenomena is the scalability property. Many complex systems – resulting from emergent dynamics – tend to be 'self-similar' across levels. That is, the same process drives order-creation behaviours across multiple levels of an emergent system (Kaye, 1993; Casti, 1994; West et al., 1997). These processes are called 'scaling laws' because they represent empirically discovered system attributes applying similarly across many orders of magnitude (Zipf, 1949). *Scalability*[2] occurs when the relative change in a variable is independent of the scale used to measure it. Brock (2000: 30) observes that the study of complexity '… tries to understand the forces that underlie the patterns or scaling laws that develop' as newly ordered systems emerge. Theories explaining PLs are also scale-free. This is to say, the same explanation (theory) applies at all levels of analysis.

Power Law phenomena exhibit Paretian rather than Gaussian distributions, as shown in Figure 15.1. The difference lies in assumptions about the correlations among events. In a Gaussian distribution the data points are assumed to be *independent-additive*. Independent events generate normal distributions, which sit at the heart of modern statistics. When causal elements are *independent-multiplicative* they produce a log-normal distribution which turns into a Pareto distribution as the causal complexity increases (West and Deering, 1995). When events are *interdependent*, normality in distributions is *not* the norm. Instead Paretian distributions dominate because positive feedback processes leading to extreme events occur more frequently than 'normal', bell-shaped Gaussian-based statistics lead us to expect. Further, as tension imposed on the data points increases to the limit they can shift from independent to interdependent. PLs are frequently '… indicative of correlated, cooperative phenomena between groups of interacting agents …' (Cook et al., 2004).

Power laws are ubiquitous. They apply to word usage, papers published, book sales, and web hits (Newman, 2005) and business firms (Stanley et al., 1996; Axtell, 2001; Park et al., 2009). Cities follow a PL distribution when ranked by population (Auerbach, 1913; Krugman, 1996), as does the structure of the Internet (Albert et al., 1999). Andriani and McKelvey (2007, 2009) list ~140 kinds of PLs that range in application from atoms to galaxies, from DNA to species, and from networks to wars.

Brock (2000) says PLs are the fundamental feature of the Santa Fe Institute's approach to complexity science. We argue that PL theories apply to management and organizations. There is good reason to believe that PL effects are ubiquitous in organizations and have far greater consequence than current management theories presume. For further insight into the growing research on Pareto and PL distributions, see Zipf (1949), West and Deering (1995), Newman (2005), and Taleb (2007).

In sum, PLs usually indicate the presence of three underlying features: (1) fractal structure; (2) scale-free (SF) causes (and SF theories); and (3) Paretian distributions (including long tails and extreme events).

Why pay attention to power-law distributions?

A recent reviewer of one of our papers took the stance of trying to defend the 'Gaussian' perspective. He/she says:

- 'Yes, firm sizes exhibit the PL. Why should we care? What is the Gaussian doing wrong?'
- 'The Gaussian treats all sizes of firms without prejudice.'
- 'Aren't PLs *i.i.d.*,[3] just with a different distribution than normal?'
- 'Most of the things that happen to us happen within 3 standard deviations of the mean.'

Some 16,000 earthquakes occur in California every year – most unfelt. But every 10–20 years a quake occurs that kills people in buildings; Californians await the 'Big One' that could do incredible damage – like the recent quake in China that killed thousands of children. Should people not care or worry about this eventuality? The current liquidity-induced worldwide recession and other market crashes occur much more frequently. Many tenured professors recently signed a *New York Times* ad (25 January 2009) saying that we should let crashes, like nature, run their course with no intervention. Yet millions of people worldwide have lost their jobs, retirement benefits, or worse.… Should we not care and try to learn how to negate these calamities? Or, oppositely, the US has some 17 million Ma&Pa stores, only one of which scaled up into Walmart. Should we ignore the extremes and just settle for studying the average?

Many managers work in industries that are PL distributed. Given this, econometric research assuming *i.i.d.* data points and focusing on ways to improve the 'average' firm offers questionable advice to practitioners. Axtell (2008) says: 'The typical firm does not exist'. Worse, many if not most firms and managers are connected to others in significant ways. Firms compete, pursue M&A activities, learn from other firms, and influence governments. Managers make decisions about hiring, firing, promoting, work in competitive contexts, learn and communicate with other managers, assert control and dominance or foster employee self-organization. Firms and managers are 'connected' in many ways; they are not independent entities – they do not behave like turnips, cornstalks or olive trees. Connected entities under tension of some sort often, if not typically, show evidence of Pareto distributions and PLs.

We believe the time has come to accept that PL phenomena are much more widespread and more problematic for firms and managers than Gaussian statisticians admit. Nobel Laureate Murray Gell-Mann (2002) goes so far as to say there are two equally important parallel 'regularities' scientists need to research:

- *Reductionist law-like regularities:* The reductionist causal processes of normal science, which are predictable and easily represented by equations – the data and information much preferred in classical physics and neoclassical economics (2002: 19). These are the point attractors of chaos theory – defined by forces, equilibrium, and energy conservation.
- *Multilevel SF regularities:* Outcomes over time that result from an accumulation of random tiny initiating events that have lasting effects, are compounded by positive feedback effects over time, and become 'frozen accidents' (2002: 20). These are the strange attractors of chaos

theory – never repeating, fostering indeterminacy, offering a different kind of regularity.

Scientific methods are well established for reductionist regularities. We believe it is time to begin developing a PLS with theory and methods specifically suited for studying scale-free regularities – a science especially relevant for researching PL distributed industries as well as PL distributions within firms.

If the 'typical' firm does not exist, as Axtell puts it, what is the point of continuing the search for statistically significant information about firms at the mean? How does studying mice help improve the survival of elephants. How does studying Ma&Pa stores help Sears/Kmart compete against Walmart? How does studying either extreme offer much value for firms near the median?

ELEMENTS OF POWER-LAW SCIENCE (PLS)

We briefly define PLS as follows. A field of inquiry and methods dealing with phenomena characterized by low to high heterogeneity, (potentially) infinite variance, scalability, and a level of connectivity that spans from low to high coupling. Such phenomena are predominantly scale-free, PL distributed (both in their spatial and temporal distribution) and obey fractal dynamics. The subjects included within the ovals of Figure 15.2 are key elements of PLS. The other fields are underlying concepts and theories complementary to PLS.

In the following we briefly discuss some of the key elements of PLS.[4]

Network science

The legendary Hungarian mathematician, Erdos, in introducing random network theory, assumed links are randomly distributed across nodes and form a bell-shaped distribution, wherein most nodes have a typical number of links with the frequency of remaining nodes rapidly decreasing on either side of the maximum. Watts and Strogatz (1998) show, instead, that networks of living agents follow the *small world* phenomenon whereby society is visualized as consisting of weakly connected clusters, each having highly interconnected members within. This structure allows cohesiveness (high clustering coefficient) and speed/spread of information (low path length) across the whole network.

Studying the World Wide Web, however, Barabási (2002) and colleagues find that the structure of the Web shows a PL distribution, where most nodes have only a few links and a tiny minority – the hubs – are disproportionately very highly connected. The system is scale-free, no node can be taken to represent the scale of the system. Defined as a 'scale-free network', the distribution shows (nearly) infinite variance and the absence of a stable mean. It turns out that most real life *small world* networks are SF (Ball, 2004) and fractal (Song et al., 2005). SF networks appear in fields as disparate as epidemiology, metabolism of cells, Internet, and networks of sexual contacts (Liljeros et al., 2001).

Contribution to PLS:

Networks point to a universal property of living systems, namely, that the structure of most systems subjected to change processes is SF (i.e., the same cause acts at multiple levels or wide-ranging sizes as measured) and is PL distributed.

Fractal geometry and calculus

Fractal geometry was developed by Mandelbrot (1982) to make sense of the rough, irregular shapes of most natural objects, from cauliflowers to coastlines, trees, and galaxies. As Mandelbrot (1982: 1) writes: 'Clouds are not spheres, mountains are not cones, coastlines are not circles, and bark is not smooth, nor does lightning travel in a straight line'. A whole cauliflower, and each of its increasingly smaller florets, sub-florets,

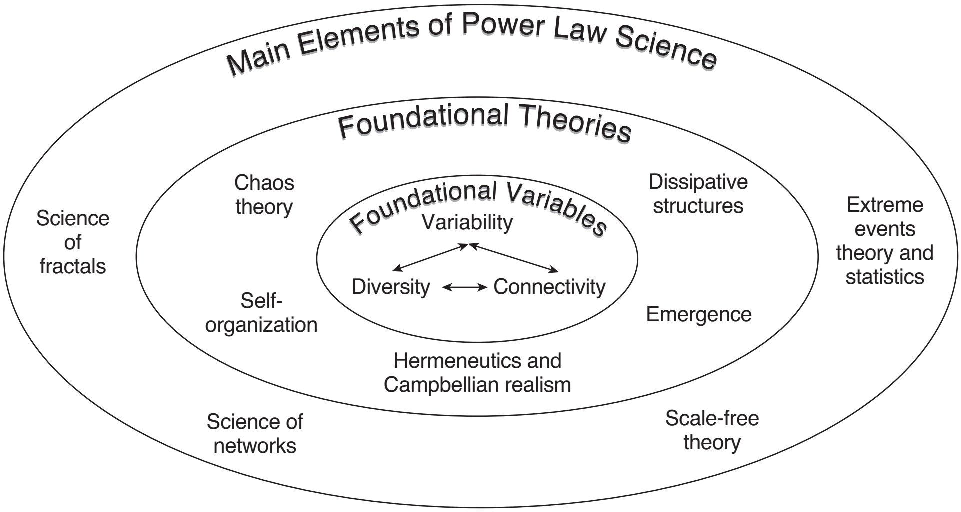

Figure 15.2 Main elements of power-law science

and so on, show the same design and shape and result from the same causal dynamics. A fractal (Mandelbrot and Hudson, 2004: 118) is: 'a pattern or shape whose parts echo the whole'. Fractals are self-similar objects. Like the cauliflower, so the Eiffel Tower: the four largest sections are made up of large trusses, which are composed of smaller trusses, etc. (Mandelbrot, 1982: 131–132).

Fractals are not idle mathematical curiosities. Fractals and PLs are found from atomic nanostructures (~10^{-10} meters) to galactic megaparsecs (~10^{22} m) – across a range of 32 orders of magnitude (Baryshev and Teerikorpi, 2002). In biology, West and Brown (2004) demonstrate a PL relationship between the mass and metabolism of virtually any organism and its components – based on fractal geometry of distribution of resources – across 27 orders of magnitude (of mass). Self-similarity is key to a fundamental property of fractals and PLs: linear scalability. PL systems do not exhibit a characteristic scale and consequently enjoy some peculiar statistical properties. Systems that scale linearly are part of a family of distributions named after the French mathematician Cauchy:

> As a result of this linear scaling, the distribution of the average of N identically distributed Cauchy variables is the same as the original distribution. Thus, averaging Cauchy variables does not improve the estimate.… This is in stark contrast to all probability distributions with a finite variance, σ^2, for which averaging over N variables reduces the uncertainties by a factor $1\sqrt{N}$. This nonstandard behavior of the Cauchy distribution is a consequence of its weakly decaying 'tails' that produce too many 'outliers' to lead to stable averages. (Schroeder, 1991: 159)

It is interesting to note that Leibnitz, the founder with Newton of modern calculus, also worked on fractal calculus, that is calculus for functions that do not have a first derivative (West et al., 2003). Over 300 hundred years ago, it was clear to Leibnitz that linear calculus was applicable to a finite range of phenomena and that science needed two types of calculus. Linear calculus moved on to become the main instrument[5] of scientific analysis whereas fractal calculus was forgotten and survived as a mathematical curiosity without real applications in the scientific community.

Contribution to PLS:

Fractals introduced scaling laws – the idea that simple generative mechanisms generate complex patterns by operating at multiple nested levels.

Scale-free theory and method

Various authors (Sornette, 2000; Kauffman, 2003; Mandelbrot and Hudson, 2004) have noticed how the development of extreme events (but also more in general radical innovations and the emergence of radical novelty in social systems; see Jacobs, 1969; Mokyr, 1998) seems to follow an explosive scaling dynamic fuelled by positive feedback and autocatalytic effects. If one looks at examples such as financial bubbles or crashes, diffusion of innovations (the ipod is a paradigmatic example), or Google's takeover of the search market, one can see that, at least in the explosive phase, some 'engines of growth' cause a scale-independent development of the system.

In Table 15.1 we present a short description of seven SF theories. In our article in *Organization Science* (2009) we discuss their application to organizational phenomena in more detail.

Early scalability recognition

Scale-free theories call for the identification of so-called butterfly-levers before extreme events occur. The opportunity or threat posed by an extreme event first appears as a tiny initiating butterfly-event[6] to which heterogeneous agents, initially endowed with zero-order connectivity, respond by searching for and connecting to other agents (Kauffman, 1993). Through such interactions, the agents' sensing processes can reach beyond the individual atomized Gaussian event to apprehend the interdependent dynamics of an extreme Paretian one. OR, they ignore the butterfly-events and then a disaster occurs. Well-documented post-mortem analyses of the events that led up to the First World War, the Challenger disaster, 9/11, Enron, and Hurricane Katrina provide us with examples where appropriate sensing-and-responding didn't happen – largely because of the suppressing effects of top-down control and organizational 'silos'. Even though individual

Table 15.1 Empirical basis of scale-free causes of power laws*

Theories	*Explanation*
Spontaneous order creation	*Heterogeneous agents* seeking out other agents to learn from so as to improve fitness generate networks; some networks become groups, some groups form larger groups and hierarchies.
Phase transitions	*Turbulent flows*: Exogenous energy impositions cause autocatalytic interaction effects at a specific energy level – the first critical value – such that new interaction groupings form.
Preferential attachment	*Nodes*: Given newly arriving agents into a system, larger nodes with an enhanced propensity to attract agents will become disproportionately even larger.
Least effort	*Language and change*: Word frequency is a function of ease of usage by both speaker and listener; this law now found to apply to language, firms, and economies in transition.
Square/cube law	*Cauliflowers*: In organisms, surfaces absorbing energy grow by the square but organism grows by the cube; results in an imbalance; fractals emerge to bring surface/volume back into balance.
Hierarchical modularity	*Growth unit connectivity*: As cell fission occurs by the square, connectivity increases by $n(n-1)/2$, producing an imbalance between the gains from fission vs. the cost of maintaining connectivity; consequently organisms form modules or cells so as to reduce the cost of connectivity.
Self-organized criticality	*Sandpiles, species adaptation*: Under constant tension of some kind (gravity, ecological balance), some systems reach a critical state where they maintain stasis by preservative behaviours – such as sand avalanches, forest fires, changing heartbeat rate – which vary in size of effect according to a power law.

* Paraphrased from Andriani and McKelvey (2009); they list a total of fifteen.

agents possessed the relevant information, organizational constraints prevented them from *networking, forming groups, performing additional analyses, taking collective action, influencing higher management*, etc.

Horizontal scalability: from Ma&Pa to Walmart

All but a very few of the 17 million Ma&Pa stores stay that way. A few, however, like Walmart, various chain stores – and in other industries, Southwest Airlines, Microsoft – scale up from very small to very large. Walmart started with Sam Walton's one store and then, without changing the formula (i.e. the way of doing business, their special ways of supply-chain management, and so on), scaled up to be the largest retail store in the world – the 'formula', the basic cause of Walmart's success, didn't change.

Contribution to PLS:

The growth of most systems follows a set of scaling trends that link tiny initiating events with more significant or even extreme outcomes.

FOUNDATIONAL THEORIES

Chaos theory

Chaos theory is a largely mathematical body of knowledge started by Poincaré in the 1880s with the discovery that groups of simple objects that obey Newtonian dynamics exhibit random behaviour that makes long-term predictions impossible (Gleick, 1987). Poincaré's thinking opened a breach into positivism that almost one century later would lead to the formulation of chaos theory (Lorenz, 1963; Feigenbaum, 1978) and to the discovery that an ordered system at the aggregate level may hide chaotic dynamics at the micro level due to sensitivity to initial conditions. Chaos theory questioned the dominant linear approach in science and introduced a number of novel concepts that to some extent have been subsumed within complexity theory. In terms of PLS, chaos theory has contributed fundamental concepts and discoveries such as the notion of butterfly effect, the fact that deterministic systems can show chaotic (hence unpredictable) behaviour and the development of mathematical tools to deal with nonlinear behaviour. Complexity theory (briefly described below) started from the ideas of chaos and randomness and showed that ordered behaviour can emerge out of randomness and chaos.

Far-from-equilibrium dissipative structure theory at the edge of order[7]

Prigogine (Nicolis and Prigogine, 1989) built on Bénard's (1901) study of emergent structures in fluids. In a teapot, for example, the 'rolling boil' familiar to chefs describes a shift from molecules dissipating heat via conduction (by vibrating faster in place) to molecules circulating around the pot, thereby speeding up heat transfer through convection. Because emergent structures serve to dissipate energy imposing on a system from outside, they are called 'dissipative structures'. This phase transition – which occurs at the so-called *'1st critical value'* of imposed energy (what McKelvey, 2001, 2008a,b, calls 'adaptive tension') – defines 'the edge of order'. This theory is predominantly from physics and is math intensive (Prigogine, 1961, 1997; Haken, 1983; Nicolis and Prigogine, 1989; Mainzer, 1994/2007; Allen, 1997).

Prigogine argues that the tension between higher and lower energy (and associated states of order) creates an energy differential that initiates agent self-organization and resultant order creation. Prigogine terms these 'dissipative structures' because they draw energy away from the surrounding, already existing, larger, 'far-from-equilibrium' order or energy conditions. They speed up entropy production by reducing the energy of the higher-ordered state and dissipating it into a lower-order state – the more entropic condition.

Prigogine uses dissipative structures to explain both the cause and disappearance of order at all levels of analysis in three ways:

1 The energy of an existing higher energy/order state is dissipated when negentropy[8] is imported into the newly created dissipative structure from the existing higher energy state. This process speeds up entropy production.
2 Within them, new dissipative structures conduct energy translations under the First Law of Thermodynamics (about conservation of energy), and as a result, dissipate their own energy since entropy is created each time there is an energy translation.
3 Dissipative structures, once created, also exist 'far from equilibrium' and, therefore, conditions exist for the appearance of even more dissipative (sub)structures. Hierarchies of additional dissipative structures may result.

Swenson (1989) observes that order creation in the form of dissipative structures occurs to maximize the speed entropy production; this is his 'Law of Maximum Entropy Production'.

Self-organization and emergence at the edge of chaos

This was initiated by Nobel Laureates Murray Gell-Mann (1988, 2002) and Philip Anderson (1972) along with Stuart Kauffman (1987, 1993), Brian Arthur (1988, 1994), and John Holland (1988, 1995), at the Santa Fe Institute. It is oriented more towards biology and the social sciences. Their focus is on heterogeneous agents interacting at what was early on called 'the edge of chaos'. This occurs at the *'2nd critical value'* of imposed energy. In between the 'edges' of order and chaos is the region of emergent complexity or what Kauffman (1993) terms the 'melting' zone of maximum adaptive capability. Bak (1996) argues that to survive, organisms need a capability of staying within the melting zone, maintaining themselves in a state of 'self-organized criticality' (defined in Table 15.1). The signature elements within the melting zone are self-organization, emergence and nonlinearity. *Self-organization* begins when three elements are present: (1) heterogeneous agents; (2) connections among them; and (3) motives to connect endogenous sources of adaptive tension – such as mating, improved fitness, performance, and learning. Remove any one element and nothing happens. Self-organization results in *emergence*, that is, new order of some kind. It boils down to:

1 a shift from the 'force-based' science of classical physics (epitomized in its foundational axiom, $F = ma$) to the 'rule-based' theory and methods of complexity science – specifically agent-based computational modelling (see Prietula; Tracy; Vidgen and Bull this volume);
2 a shift from the positing of independent agent behaviours and Gaussian distributions to interdependent, mutual causal behaviours and consequent Pareto distributions (PLs), unstable means, potentially infinite variances, and reflexivity;
3 a shift from normal science and 'normal distribution' methodology and robustness tests against leptokurtosis to full acceptance of PLs, fat tails, extreme events, and order creation.

Talking pigs, abduction, hermeneutics and coherence theory[9]

In recent works, Boisot and McKelvey (2007, 2010) position complexity research between the inductive reasoning favoured by Postmodernists and the deductive analyses of Modernists. The former revel in the richness of many degrees of freedom (one definition of complexity) and the latter reduce phenomena to the few degrees of freedom that make the math tractable and promulgate predictive studies. This is where Gell-Mann's 'effective complexity' enters the picture – like Goldilocks' porridge, the goal is to get complexity 'just right' – neither too few nor too many degrees of freedom.

In organizational research Ketokivi and Mantere (2007) show that in conventional organization science, progress over time rests on a cycling between inductive and deductive reasoning, usually with several researchers involved. One way of taking advantage of both deductive and inductive methods is via abductive reasoning. They show that deductive reasoning often involves inductive stages and inductive reasoning often involves deductive stages. *Abduction* starts from a collection of heterogeneous facts and infers the most plausible pattern that they make – *inference to the best explanation* (Peirce, 1935). Abduction depends on the coherence with which events can be related to each other.

Siggelkow (2007) makes the point that when a single case is so unique an extreme outcome – like a '*talking pig*' – the attempt at explanation is so compelling that it stands as a telling piece of research even if it is only an *N* of 1. In Pareto distributions we often have a single extreme outcome like the Indian Ocean Tsunami, Hurricane Katrina, or the Challenger, Pioneer and Enron disasters, or positive outcomes: Microsoft, Walmart, or Google. These events are unique but worth understanding: they are *talking pigs*.

We suggest that in a Pareto world, single cases can be better analyzed via the methods of triangulation, hermeneutics and abductive reasoning. For instance, the Honda case is a classic example where single observers at different times offer different explanations of Honda's success. The question is: Can a researcher choose several observers from different disciplines, have different training, different theoretical perspectives, biases, and so on, without bias?

Triangulation

Years ago, Campbell and Fiske (1959) argued that more than one method should be used to separate possible method-induced variance from variance in the sample – so-called 'multitrait-multimethod' research (Jick, 1979). A triangulation approach used with multiple observers is stronger than a multitrait-multimethod approach by one observer; each would be better at a particular method.

Hermeneutics

Multiple observers is what hermeneutics calls for. And then the *principle of charity* must be applied; no observer has more influence than any other – at the start at least. Given this, the hermeneutics process begins working towards a *coherence theory* offering the best explanation.

Abductive reasoning

Multiple observers may apply abductive reasoning in both *Hansonian* (Hanson, 1958; Paavola, 2004) and *Harmanian* (Harman, 1956) fashion. In *Hansonian* abduction they attempt to create the best inductively-induced explanation of a single case. If it is a one-of-a-kind 'talking-pig' we can conclude that their hermeneutics approach is superior to any other single-case research method and that it is unlikely a better explanation would be forthcoming, though there is always the possibility that their principle of charity was not working and there was bias in the selection of the observers. Given this, a subsequent hermeneutics application could produce a different explanation. This leads right into *Harmanian* abduction, in which the abductive/hermeneutic process continues over time with multiple groups.

APPLICATION OF POWER-LAW SCIENCE

PLS has already impacted on a number of areas and generated entirely new approaches to the study of economic and business phenomena. We mention several.

Econophysics

The application of complexity-inspired mathematical tools derived from nonlinear physics to economics and especially finance has caused the emergence of a new discipline called Econophysics. Econophysics has moved from Pareto's initial intuition about

PL-distributed wealth distribution in Italy and now generalizes Pareto's finding to other economic and financial phenomena.

Econophysics (West and Deering, 1995; Mantegna and Stanley, 2000) focuses on the *outcomes* of self-organization and emergence, that is, new order, and the causes of fractal structures. Econophysics also brings scalability (Brock, 2000), PLs (Casti, 1994), and SF theories (Zipf, 1949) into prominence in economics and finance (Yalamova and McKelvey, forthcoming). According to Holland (2002) we recognize emergent phenomena in multi-level hierarchies, in intra- and inter-level causal processes, and in nonlinearities. Nonlinearity incorporates two key outcomes: the *butterfly-events* and *scalability*. Holland (2002: 29) says: '… Almost all *cas* [complex adaptive systems] exhibit *lever-point* phenomena, where "inexpensive" inputs cause major directed effects in the *CAS* dynamics'. These triggers, what we call butterfly-events, extend across multiple levels. A butterfly-effect sets off a nonlinear outcome when a single event out of myriad very small ones gets amplified so as to generate an extreme outcome.

The 'other' long tail of micro-niches

Ordinarily, one might think that we would find large populations well suited to Gaussian assumptions at the upper left of Fig. 15.1 – the 17 million Ma&Pa stores, 7-Elevens, etc. In the case of 7-Eleven outlets they are all the same by design. Pretty much the same for Walmart, Sears, McDonald's, and TESCO in the UK. These kinds of stores aim to stock only 'hit' products aimed at 20% of the market.

But in his book, *The Long Tail*, Anderson (2006) shows that as the Internet has lowered the cost of marketing, need for stores and shelf space, and made customer searches for idiosyncratic products much easier, a *new* long tail is developing at the upper left of a Pareto distribution. In the case of books and various other products, Amazon, for example, now makes it possible for sellers to make profits selling idiosyncratic products to idiosyncratic customers. When distribution, marketing, and search become cheap and easily available, markets develop a long tail of proliferating idiosyncratic niches containing fewer and fewer customers. This alters the balance between hits and micro-niches, thereby causing the emergence of 'unconstrained' markets which show both tails of a Pareto distribution: the long tail of the 'hit' (i.e. very popular) product niches and the long tail of idiosyncratic micro-niches.[10] The application of the 80/20 rule is therefore transformed.

In the traditional economy, a minority of products (the 20%) generates the majority of revenues (~80%) and virtually all of the profits. In an economy of many micro-niches, every product generates some profit even if sold only once. Assuming that the new Internet-based markets with *physical plus virtual* distribution channels carry 10 times as many products as the physical distribution chain (i.e. the former's 100% becomes 10% in the new markets), the hits (now down from 20% to 2% of the products) still account for a significant proportion of revenues and profits; but now the previously unprofitable 80% (the virtually-created micro-niche tail) generates about the same amount of profits. The result is the transformation of the 80/20 rule. The new interpretation is still based on the Pareto distribution, but each tail generates about the same amount of profits.

What can we conclude from this? First, the natural shape of unconstrained markets is Paretian with two long tails: (a) high-volume hits comprising one extreme; and (b) a long tail of heterogeneous micro-niches at the other extreme. Second, business models appropriate for opposite ends are very different. The most successful cases of the past 10 years – the Googles, eBays, and Amazons – are extreme events that have developed business models appropriate for what was the '80% tail' of the Paretian distribution. Third, Anderson shows that the double-tailed distribution of micro-niches and 'hits' holds across sectors (music), genre (classical music), sub-genre (chamber music), and so on.

In other words, nested Pareto distributions give rise to self-similar markets, which are expressed by the statistical regularity of PL distributions.

Tools

> … Then power laws emerge – nature's unmistakable sign that chaos is departing in favor of order… The road from disorder to order is maintained by the powerful forces of self-organization and is paved by power laws. It told us that *power laws are the patent signatures of self-organization in complex systems* (Barabási 2002: 19; our italics).

If Barabási is right, and we think that there is enough evidence to state that self-organization and PLs are related, then we ask whether we can use PL distributions as a leading indicator of self-organization in action. But what exactly does the finding of a PL indicate?

Essentially we have three problems when dealing with PLs as indicators:

First, the (high-rank) tail (usually on the X axis) of the distribution (which usually is its most important part, as it is where the extreme events occur) is characterized by low frequency and high magnitude value. While these 'outliers' are unique, they are also important. They can't just be dismissed as random events or measurement errors. Consequently, the attribution of the tail to a distribution (PL, lognormal or other) becomes difficult.

Second, how to interpret a distribution that is not a straight line and shows different behaviours? In the econophysics literature (e.g. Goldstein et al., 2004; Newman, 2005; Clauset et al., 2007), the usual responses are either to argue that the distribution is not a PL at all but some other kind of distribution (such as lognormal, exponential, stretched exponential, etc.), or truncate the distribution, saying that part (usually one end) of it follows a PL, but the rest fits some other distribution (Clauset et al., 2007).

Third, Sornette (2000), Newman (2005) and Andriani and McKelvey (2009), show that there are multiple mechanisms that generate PLs. In this chapter we have discussed some PL generative mechanisms that we call SF theories. However, SF theories are based on a set of very diverse generative mechanisms. Given this diversity, one could conclude that the finding of a PL doesn't indicate much. In Table 15.1 we have briefly defined seven SF theories most easily applying to organizations. We notice, first, that all generative mechanisms are based on historical processes and consequently that PLs are rooted in path-dependent dynamics. Second, most SF mechanisms require some kind of interdependence among data points. Third, most SF mechanisms generate fractal structures. This is to be expected as PLs indicate self-similarity. Also, as Mandelbrot (1982: 39) shows, the fractal-generation formulas – e.g. $D = \log N / \log(1/r)$ – are log formulations, which of course mirror the log-scales used to graph PLs. *Fourth,* though most SF theories point to the presence of bottom-up self-organization, others do not. To sum up: We think that the emergence of PLs sends a strong message about the features of the system under analysis. If one excludes the random walk mechanism, then all the other theories show strong commonalities. Namely, these systems are characterized by path-dependent evolutionary processes that give rise to interconnected self-similar nested structures. The patterns of distributed connectivity within and across levels is at the origin of the extreme variability and quasi-unbounded diversity that create the potential for tiny-initiating events to trigger self-organizing patterns that may escalate into extreme events. Building on Barabási, we advance the proposition that PLs are useful indicators of emergent self-organization properties in complex systems – but they indicate other kinds of PL order-creation dynamics as well.

Example tool: PLs as indicators of self-organizing economies and industries

One use of PLs as indicators is suggested by McKelvey (2011): PL-distributed cities

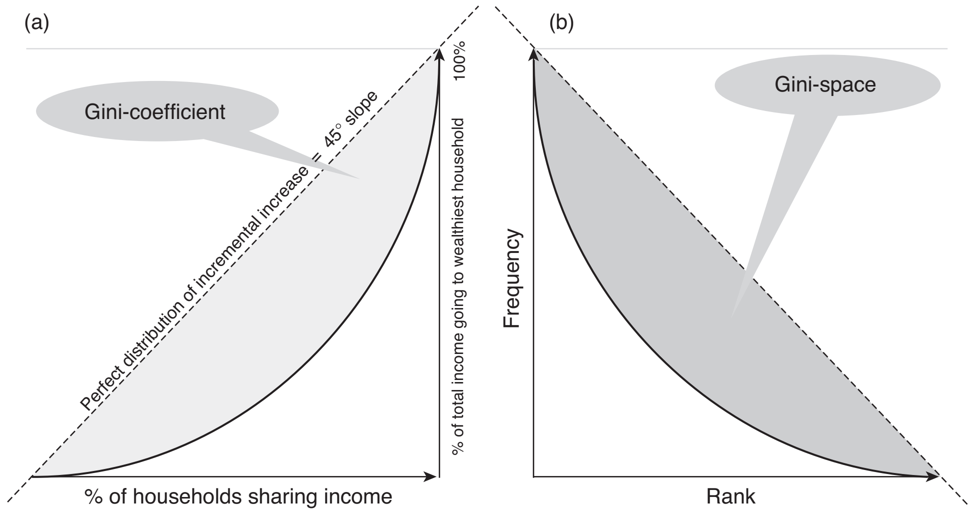

Figure 15.3 (a, b) Gini index on left; power-law 'deviation' indicator on right

may signify self-organizing economies (Krugman, 1996).[11] The Gini index illustrates this idea – shown in Figure 15.3(a).[12] The larger the curved section, the more income inequality in a society. In Figure 15.3(b), the main diagonal is reversed so that it parallels an inverse sloping PL. Given this, the more that a city rank/frequency falls below the PL 'diagonal', the less efficaciously adaptive a country's economy appears to be.

In his *Cities and Complexity*, Batty shows that while US cities fit a PL, cities in the UK do not (2005: 464; based on 1990–1991 data). Based on more recent data (dated 2005)[13] Figure 15.4 compares the UK with hot economies in India, Ireland and Slovenia.[14] As you can see, the UK shows the largest Gini index equivalent (total 'Gini space' – light gray – between city locations and the PL line) – it is the largest Gini index equivalent shown in the ~50 cityscapes of which McKelvey has created PL distributions.[15] Figure 15.4 also shows the 'Malta line' (dotted) which is nearly vertical – showing a pretty dead economy. Outside of London, the next 50+ UK cities line up pretty well along the 'Malta line'.

Is the UK as economically 'broken' as the PL equivalent of the Gini coefficient suggests? Outside of London, the UK shows considerable evidence that self-organization towards a 'good' economy is lacking.[16]

- London's GDP growth rate at the time was 33% higher than for the UK as a whole.
- The Midlands (where most of the frozen cities are) was traditionally the industrial base of the UK; it has lost some 1.1 million manufacturing jobs since 1995 (*London News*, Sept. 6, 2006).

In contrast, in 2005 Ireland shows six cities growing close to the same 'hot' rate as London (the dot–dash line is at the same 'hot-self-organizing-economy' slope as between London and the next UK city). Slovenia, another hot economy in Europe, also shows a PL slope on the 'hot' side, as opposed to the 'Malta line'. Perhaps we are on the verge of being able to use PLs as indicators of the economic viability of disparate regions and cities within national economies.

RESEARCH AGENDA

We believe that PLS will establish itself as an important field within management and

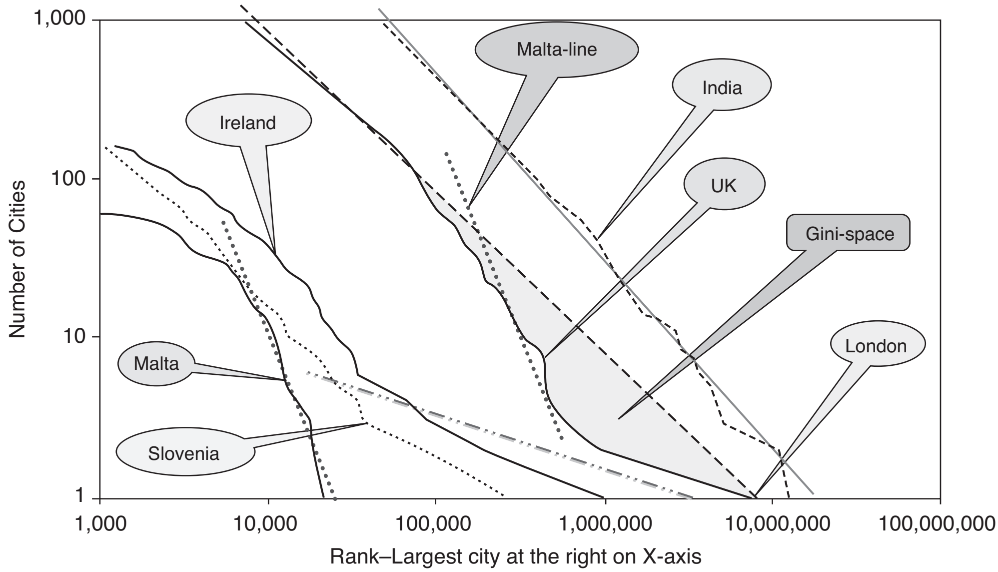

Figure 15.4 Selected city rank/size PL distributions

organizational research by pursuing the following research avenues: *First,* the ubiquity of Pareto distributions across all types of distributions within social sciences is striking. Mandelbrot and Hudson (2004: 170) wrote that:

> The cotton story shows the strange liaison among different branches of the economy, and between economics and nature. That cotton prices should vary the way income does; that income variations should look like Swedish fire-insurance claims; that these, in turn, are in the same mathematical family as formulae describing the way we speak, or how earthquakes happen – this is, truly, the great mystery of all.

In the nearly 100 years since Auerbach's finding, we do not have a theory that explains how organizations and social systems evolve towards a state characterized by PLs; given this, Krugman (1996) calls them 'spooky'. We can speculate that SF theories, emergent properties, self-organization, fractal growth, butterfly dynamics, etc. have to be part of the story, but, the theory, specifically, of why PL distributions appear is still missing. Developing such a theory will be a major task if PLS is to become accepted by management scholars; they will have to formulate PL theory to complement the *resource-based view, transaction-based view*, etc. of organizations.

Second, although we claim that in most cases Gaussian statistics represents a reductionist attempt to oversimplify reality and provides only 'an illusion of control' (Makridakis et al., 2009), the alternative we have – Paretian statistics and Paretian analytical tools – is nowhere near the Gaussian option in terms of sophistication and 'user-acceptance'. In other words we lack a fully developed alternative. The mathematics of PLs and fractals is limited in its extension and maddeningly complex. We can learn a considerable amount from disciplines that have adopted a Paretian approach, such as seismology or econophysics, just to name a couple; but it will still be necessary for quantitative social scientists, on the one hand, to learn to apply the existing Paretian tools and develop new ones, and, on the other, to identify the kind of problems that are amenable to solution via Paretian analysis. Moreover, between the extremes of Gaussian and Paretian there is a large world of distributions that covers the space between independent-additive (Gaussian) and interdependent-multiplicative (Paretian).

Third, we need to develop rules to understand when a certain social problem is more likely to be approximated via a Gaussian vs. Paretian approach. On the epistemological front, we suggest scalable abduction as a valid Paretian approach, as Boisot and McKelvey (2010) advocate.

Fourth, a low hanging fruit for PL oriented management researchers is the topic of resilience of organizations (Hollnagel et al., 2006). According to traditional approaches, systems are stable if they have some inbuilt flexibility around the normal operation point. These approaches are ultimately rooted in the concepts of equilibrium and homeostatic control. Alternative approaches stress, instead, that resilience is closer to a dynamic capability than to a fixed-point control theory (where negative feedback stabilizes the system around equilibrium). Allometric control theory (West, 2006)[17] is an example of this line of attack. It shows that resilience is essentially a consequence of the system's multi-level diversity and connectivity. Shocks are contrasted and neutralized by redistributing their impact over multiply connected and nested levels, which absorb and respond on different temporal and spatial scales. These responses are integrated by the dynamics of competition and cooperation due to inter and intra level connectivity patterns. It is the mutualism between the locally nested dynamics that generates resilience. In this vision, resilience is an emergent property of the fractal structure of the system. Building from Ashby (1956), McKelvey et al. (2010) refer to this as 'requisite fractality'; they draw empirical support from nineteen biological studies of predator/prey fractals, which appear as 'M& A waves' in the business world (Park et al., 2009) This implies that a simple way to assess the potential resilience of organizations is to calculate the fractal (or multifractal) dimension of the organization. This amounts to calculating the number of levels over which a shock can be distributed (or an innovation designed), their interconnections and their diversity. A similar approach could be applied to larger units such as economies.

Fifth, PLs can be used as indicators of self-organizing dynamics. In general, the presumption is that healthy ecosystems are self-organizing and therefore exhibit PL effects, fractal structure, and SF dynamics. This suggests, in turn, that well-functioning self-organizing processes – increasing connectivity and SOC (Self-Organized Criticality, (Bak, 1996)) under adaptive tension – underpin economic self-organizing success, as Ishikawa (2006) and Podobnik et al. (2006) have found elsewhere. One can speculate that in a self-organizing economy, the pattern of distribution of resources (for instance as revealed by city-size distribution) a PL distribution may signify well-working economies. Could the foregoing self-organization theory of what underlies good economies be extended to industry ecosystems? More generally, can PLs be used as indicators of emergence in action?

Sixth, the occurrence of PLs is explained by SF theories; we have listed a few in Table 15.1 – they come from physics, biology and social science. SF theories offer the promise of explaining extreme outcomes and reducing the fragmenting effect of social science disciplines on organizational research. Discipline-centric researchers may dislike this consequence; discipline-neutral researchers will see research advantages and practitioner relevance.

Seventh, research on extreme events can profit from PLS. SF theories may provide the key to differentiate between scalable and non-scalable TIEs. Andriani and McKelvey (2010) highlight the phrase, 'You can't see what you aren't looking for'. The potential contribution to strategy and entrepreneurship deriving from the identification of butterfly-levers before extreme events occur is significant. The opportunity or threat posed by an extreme event first appears as a small butterfly-event to which heterogeneous agents, initially endowed with zero-order connectivity, respond by searching for and connecting with other agents (Kauffman, 1993), which may then spiral into multiplicative interdependence and PLs.

CONCLUSION

The dramatic transformations in the field of business, economics and finance have confirmed what Schumpeter (1939: 102) anticipated long ago:

> We must recognize that evolution is lopsided, discontinuous, disharmonious by nature – that the disharmony is inherent in the very modus operandi of the factors of progress.… The history of capitalism is studded with violent bursts and catastrophes… more like a series of explosions than a gentle, though incessant, transformation.

The quote above describes the world that Power-law Science aims to understand. The *disharmony* Schumpeter refers to represents the unbounded diversity and the agents' heterogeneity that are at the same time revealed by both tails of PL distributions and causes of the same distributions. This *disharmony*, then, becomes the engine via connectivity of the 'violent bursts and catastrophes' (in modern parlance, extreme outcomes). These have always characterized the world managers live in but the dominance of linear thinking, Newtonian equilibrium, Darwinian gradualism and the statisticians' *i.i.d.* assumption in both natural and social sciences has metaphorically pushed the issue of extremes 'under the carpet': 'outliers' causing skew distributions are demoted to random (meaningless) events that can be disregarded. The financial-economic crisis, which started in the US in August 2007, has made all too clear that change is long due. Even a recent issue of *The Economist* (18 July 2009) shows on the cover page a melting book titled *Modern Economic Theory*. The accompanying editorial is: 'What went wrong with economics'. In this chapter we suggest that Power-law Science offers a new direction to tackle some of the issues that have plagued organization science and economics.

NOTES

1 The Principle of Superposition holds that: 'The net response at a given place and time caused by two or more stimuli is the sum of the responses which would have been caused by each stimulus individually. … In mathematics, this property is more commonly referred to as additivity. It applies to all linear systems'. Quoted at http://en.wikipedia.org/wiki/Superposition_principle

2 Peter Allen, one of the editors of this volume takes a somewhat different view (private communication) that in 'any dynamical system with growth and decline, then there will quite obviously be an element of a power law emerging providing that the probability of decline is actually greater than that of growth. This means that such systems are 'fed' by newcomers. … The pure, simple, scale-free power law indicates simply that these probabilities of growth and decline are not really functions of size'. 'However, a system of probabilistic growth and decline can perfectly well indicate a peaked distribution around some average population size, if the probability of growth and decline are functions of population size – such as in a logistic equation, where small populations grow and populations above the "carrying capacity" decline.'

'In considering the probability of extreme events – then the simple, UNJUSTIFIED assumption by economists of a Gaussian is clearly completely unjustified. Extreme events will be better described by any dynamic probability model that discusses growth and decline. SO, particularly for extreme events, it is important to realize that the probability distribution is NOT GAUSSIAN but has a precise form dictated by the different terms representing mechanisms involved in growth and decline. In very simple models with scale-free parameters you will have a pure power law distribution. But in most cases this is only the first approximation to a more complex truth.'

3 *i.i.d.* stands for independent and identically distributed data points – like cornstalks, olive trees, heights of giraffes and human bodies etc.

4 Due to space limitations we omit discussion of Extreme Statistics Theory; Baum and McKelvey (2006) offer a management-relevant introduction to this topic.

5 Calculus and analytical functions became so reified that the French mathematician Hermite wrote: 'I turn with terror and horror from this lamentable scourge of continuous functions with no derivatives' (from a letter to Thomas Stieltjes in 1893;

Wiki source: http://74.125.155.132/search?q=cache:9G4dsfcxgCYJ:en.wikipedia.org/wiki/Charles_Hermite+Hermite+%22I+turn+with+terror+and+horror%22&cd=1&hl=en&ct=clnk&gl=us

6 The 'butterfly' appellation stems from a paper by E.N. Lorenz (1972) titled 'Predictability: Does the flap of a butterfly's wings in Brazil set off a tornado in Texas?'

7 For further discussion of basic complexity science concepts and theories, see various prior chapters in this volume.

8 Schrödinger (1944) coined *negentropy* to refer to energy importation (Nicolis and Prigogine, 1989).

9 For an expanded discussion of hermeneutics, abductive reasoning, and scalable abduction, see McKelvey and Benbya (2007).

10 Brynjolfsson et al. (2006) show that the micro-niche long tail is explicitly due to Internet marketing.

11 Chou and Keane (2009) illustrate this idea further in showing how PLs of four Web-oriented industries suggest where M&A and management changes could take place.

12 The Gini coefficient is a measure of country-level income inequality. A good definition is offered at: http://en.wikipedia.org/wiki/Gini_coefficient from which we take our reproduction (accessed 11 April, 2008). The larger the Gini coefficient, i.e. the larger the area within the curve, the worse income inequality.

13 Cities are plotted by rank (biggest to smallest) and population size. The city-population data for 2005 data come from http://population.mongabay.com/ (accessed 31 March, 2007). Rather than use 'binning' or 'cumulative probability' to make the line look straighter, we use the 'Gini space' as an indication of economic weakness.

14 Though not shown, cities in the US, Japan, and China show a strong PL fit with the 2005 data, as does India, which is shown in Figure 15.4.

15 The '50' includes the EC 27, and other industrialized or commodity-based economies leaning in the 'hot' direction.

16 For further discussion, see McKelvey (2011).

17 Allometric control theory '…has a built-in long-time memory reflected in its inverse power-law character… (p. 210). This memory implies that the allometric control does not only respond to what is happening now, but it also responds to what happened in the past' (p. 264). This is important as it means that systems can adapt to their environment by incorporating in their control process external stimuli. In its simplest form an allometric control can be '… regarded as resulting from the balance between two antithetical sets of behaviour. … These are, repulsion behaviour, which results from the selection pressure for individuals to maximize their resources and hence to separate, and attraction behaviour, which results from the selection pressure to make the maximum use of available resources and hence to congregate wherever these resources are currently most abundant' (this latter quote is taken from Taylor and Taylor, 1977: 185).

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PART II

Applications

A

Complexity and Organizing

16

Complexity and Organization–Environment Relations: Revisiting Ashby's Law of Requisite Variety

Max Boisot and Bill McKelvey

INTRODUCTION

It is a commonplace of organization theory that organized systems must adapt to their environment in order to survive (Lawrence and Lorsch, 1967; Aldrich, 1979). The cybernetician, W. Ross Ashby (1956) is perhaps best known for his *Law of Requisite Variety*, which framed the internal order generated by a system as its response to impinging environmental forces (Ashby, 1962). In this chapter, we recast Ashby's law as the *Law of Requisite Complexity* (McKelvey and Boisot, 2009). The latter holds that, to be efficaciously adaptive, the internal complexity of a system must match the external complexity it confronts.

Current thinking holds that organizations can invest in adaptation in two ways: (1) simplify the complexity of incoming stimuli so as to economize on the resources that need to be expended in responding; (2) invest more resources in the response than they judge to be strictly necessary so as to ensure some degree of adaptation. The risks associated with the first approach are those of oversimplification – i.e. unfamiliar stimuli merely get assimilated to familiar ones and hence get mis-classified. The risks associated with the second are that resources get depleted by unnecessarily complex responses before adaptation occurs. To explore the trade-offs a system faces between stimulus simplification and response complexification, we draw on complexity theories to develop a conceptual framework, the *Ashby Space*, that can help researchers and practitioners to frame the challenges of adaptation in resource-efficient ways. We first briefly review key aspects of general systems theories, early organization theories, and complexity theories. We then draw on Ashby's *Law* to create the Ashby Space and illustrate its use by applying it to the 2007 liquidity crisis.

SYSTEMS, ORGANIZATIONS, AND COMPLEXITY: A REVIEW

General systems theory

Our point of departure is a living cybernetic system capable of responding to its environment in adaptive ways, defined as the class of systems behaviours that contribute to the maintenance of system identity in the face of external perturbations (Churchman and Ackoff, 1950). Cybernetics was defined by Wiener (1948) as the science of control and communication in the animal and the machine. All living and most mechanical systems are sustained by the presence of positive and negative feedback loops; the first amplifying and the second dampening information-bearing signals of relevance to them. The study of negative feedback in general systems theory (GST) showed how systems acted to preserve themselves under changing external conditions. The distinction between the system's interior and its exterior is essential to the preservation of a system's identity and continued survival under conditions of environmental change. Through the mechanism of *homeostasis* (Ashby, 1956), a system is able to maintain an 'internal' equilibrium in the face of 'external' perturbations. Yet systems are also capable of generating change autonomously by amplifying feedback instead of merely adapting to external contingencies by dampening it – an idea that took root in GST with Maruyama's (1963) classic paper on deviation-amplifying positive feedback processes.

Organizations in environments

The cybernetic systems discussed by Wiener and others (Buckley, 1968), exhibited minimal complexity. They were designed to respond to a limited range of external contingencies, and to do so primarily through negative feedback processes. Human organizations, by contrast, are capable of dealing with a massive range of external contingencies, far exceeding those that an individual human being, let alone a simple cybernetic machine, can handle. Yet for most of the twentieth century human organizations were conceived of as simple machines, tightly controllable by their creators or owners (Taylor, 1911; Fayol, 1916; Koontz and O'Donnell, 1964) and hence predictable in their behaviour. Etzioni (1961) analyses an organization's capacity to secure compliance in carrying out complex tasks through the exercise of *power* expressed via hierarchical authority relations, suggesting that, in the human case, this capacity is what distinguishes internal from external organization – a distinction that was later taken up by the markets and hierarchies framework (Coase, 1937; Williamson, 1975). With internal organization, the exercise of power allows multiple negative feedback loops to be brought under some central control in order to achieve stability and a unitary agency.

The passage from a mechanistic to a more organic conception of human organization (Burns and Stalker, 1961) had taken place by the early 1960s, partly in response to the discovery that human organization was neither as controllable nor as predictable as had been assumed (Trist and Bamforth, 1951; McGregor, 1960). The systemic processes that demarcated a lower-entropy[1] internal organization from a higher-entropy external environment were not all under managerial control. Nevertheless, through evolution, and in contrast to a purely mechanical system, an organic system could *learn* to maintain a distinction between internal and external environment, preserving a boundary and exercising some measure of control over what crossed the boundary (Miller, 1978). Homeostasis could thus be maintained inside the boundary across a wider range of environmental changes than in the case of a purely mechanical system. An *intelligent* organic system could then take this adaptive capacity one step further by generating representations of both its internal and external environment (March and Simon, 1958). These could be manipulated so as to allow it to anticipate and respond to the future states of both.

The organic conception of organizations emerged alongside the new GST being formulated in biology, itself aspiring to the status of 'a general theory of organization' (Bertalanffy, 1968: 34; Kast and Rosenzweig, 1973). A cybernetic system could now be viewed as a special case of a general system, one that was equilibrium-seeking. A subset of these – *autopoietic* systems – exhibited the property of self-organization (Maturana and Varela, 1980), exploiting the dampening and stabilizing effects of negative feedback effects to achieve autopoietic closure. The interior of any autopoietic system will always be characterized by a lower level of entropy than that of its environment. Indeed, for many biologists, this entropy differential actually *defines* organization (Brooks and Wiley, 1988; Weber et al., 1988).

A number of scholars then began to study the way that the structures and behaviours of organized human systems adapt to changes in the environment (Woodward, 1958; Lawrence and Lorsch, 1967; Thompson, 1967). An environment experienced as complex provokes a matching process of differentiation and integration in such structures and behaviours; one experienced as simple, less so. In these contingent responses of an organized system to the characteristics of its environment, we have, in effect, a first social science application of Ashby's *Law of Requisite Variety* (1956): an adaptive system survives to the extent that the variety it generates matches that of the environment it finds itself in. In what could then be seen as a further application of Ashby's law, Perrow (1972) framed the issue of organizational complexity in terms of the *tasks* that human organization has to perform, characterizing task complexity by its resistance to both routinization and understanding. For Perrow, complexity had both an objective and a subjective side, that is, it can be inter-subjectively ascertained to be a property of the environment itself (objective complexity) or it can describe an individual's experience irrespective of the objective properties of the environment (s)he encounters (subjective complexity).

Complex adaptive systems

The foregoing view assumes that organizations are *objects* in an environment that can be treated as a *residual* category – i.e. it comprises everything that the organization is not. Yet *we,* either as external observers or as members of organizations, are the ones who decide where to place boundaries around 'the' organization and hence who define what we will treat as residual. *We* then see the environment as having higher levels of entropy because we ignore the degree to which it is itself organized and capable of exerting force on organizations. The emergence of far-from-equilibrium thermodynamics (Prigogine, 1955; Prigogine and Stengers, 1984), and of the *complex adaptive systems* (CAS) perspective in the 1990s, however, challenged this stability-seeking, 'object-oriented' view of organization.

The first phase in the development of the CAS perspective can be traced back to the physicist Erwin Schrödinger, who, in a small book called *What is Life?* (1944), had suggested that life self-organizes by sucking in low entropy from its environment and spitting out high entropy back into it. Prigogine and his co-workers in Europe, building on Bénard's (1901) study of emergent structures in fluids, then further postulated that new order – and, by implication, organization – emerged from a speeding up of such entropy production (Swenson, 1989). Prigogine labelled the resulting organized entities 'dissipative structures'. In a teapot, for example, the 'rolling boil' familiar to chefs describes a shift from conduction – homogeneous molecules dissipating heat by vibrating faster in place – to convection – molecules circulating around the pot. The shift speeds up heat transfer and in so doing more efficiently reduces an imposed energy differential. This phase transition, which occurs at the so-called '1st critical value' of imposed energy – McKelvey (2001) calls this an *adaptive tension* – defines an 'edge of order' (Haken, 1977; Mainzer, 1994/2007). Living 'dissipative' systems become increasingly efficient and exploitative of their environment, indeed, in some cases so much so that at the 'edge of order', many lose their capacity to adapt and die (Miller, 1990).

A second phase, more focused on living systems, was initiated by Anderson (1972), Gell-Mann (1988), Holland (1988, 1995) and Arthur (1994) at the Santa Fe Institute in New Mexico. These scholars explored the behaviour of heterogeneous agents interacting at the so-called 'edge of chaos', a state that emerges at a '2nd critical value' of adaptive tension. At this value, a second phase transition occurs from the order that appeared at the 1st critical value to chaos. Between the 'edges' of order and chaos lies a region of emergent complexity, or what Kauffman (1993) terms the 'melting' zone. It is a zone in which adaptive capability is at its maximum. Bak (1996) argued that to survive, entities need to maintain themselves near the edge of chaos, i.e. in the melting zone, in a state of 'SELF-ORGANIZED CRITICALITY',[2] one in which the entity achieves and then maintains an efficaciously adaptive state under changing environmental (or even internal) conditions. A process of self-organization is initiated when heterogeneous agents in search of improved fitness interconnect under conditions of exogenously or endogenously imposed adaptive tension. New order is an emergent outcome of this process.

A third phase, driven by the new discipline of econophysics, is now underway, focusing on the *outcomes* of self-organization and emergent new order. According to Thietart and Forgues (this volume), Prietula (this volume) and Tracy (this volume), emergent phenomena appear in the nonlinear, intra- and inter-level causal processes of multilevel hierarchies. Nonlinearities are a source of *butterfly-effects*[3] and *scalability*, extending across multiple hierarchical levels within organisms and other organized entities. Butterfly effects, which are tiny initiating events (i.e. Holland's 'lever points' (1995: 5)) that can produce extreme outcomes such as hurricanes, stock market crashes, giant firms, etc., can be expressed in power law form (Zipf, 1949; Newman, 2005). Scalability (Brock, 2000) and scale-free causes (West and Deering, 1995; Andriani and McKelvey, 2009) are best understood by considering a cauliflower. First cut off a 'floret' and then cut a smaller floret from the first; keep cutting successively smaller florets in this way. Each will be smaller than the former, but each will exhibit the same shape, structure, and genesis. Scalability reproduces the same 'fractal' structure[4] at different scales (Mandelbrot, 1982); which is to say that scale-free causes generate the same dynamic, effect, or characteristic at multiple levels of a system.

In what follows we take organizing to be an emergent far-from-equilibrium phenomenon that neither entails nor precludes the existence of 'organizations' as stable objects. The latter occupy one end of a continuum along which a range of organizational phenomena can be located. Order-creation via the amplification of positive feedback at one level of an organization becomes as important as equilibrium-seeking via the damping effects of negative feedback at another. When working in tandem, both contribute to the 'organizing' process; hence both can be adaptive. We now explore this point further by means of the Ashby Space.

ASHBY'S LAW AND THE ASHBY SPACE

Ross Ashby, one of the founders of GST, was interested in the range or variety of situations that an animal or a machine could respond and adapt to. His *Law of Requisite Variety* states that 'only variety can destroy variety' (Ashby, 1956: 207): a system survives to the extent that the range of responses it is able to marshal – as it attempts to adapt to imposing tensions – successfully matches the range of situations – threats and opportunities – confronting it. In the case of a living system, the response might be wholly behavioural and often outside a system's cognitive control – as in the case of a hormonal response or a reflex. Alternatively the response might be a blend of behaviour and cognition that is contingent on the system classifying a stimulus as foreshadowing, say, the presence of a foe and requiring a fight-or-flight decision. It will then respond to *representations* of its environment that are constructed out of such classification activity rather than to its environment directly (Plotkin, 1993). Gell-Mann (2002: 16–17; see also Maguire this volume) sees representations as *effectively complex* 'schemas' – structured descriptions of an objective external world which incorporate neither too few nor too many degrees of freedom. What advantage do schemas confer?

If it is not to waste its energy responding to every will-o'-the-wisp, a system must build schemas in ways that distinguish meaningful information (stimuli conveying 'important' real-world regularities) from noise (meaningless stimuli). In other words, it must distinguish between what Gell-Mann has labelled 'effective' and 'crude' complexity (Gell-Mann, 1994). Note that what constitutes information or noise for a system is partly a function of the system's own expectations and judgments about what is important (Gell-Mann, 2002) – as well as of its motivations – and hence, of its models of the world and its intents (Dennett, 1987). Valid and timely representations (schemas) economize on organism's scarce energy resources (Ball, 2004; Vermeij, 2004). This can even be seen in how we use language. Zipf (1949) showed how the frequency of word use inversely correlates with word length. The resulting power law distribution established a PRINCIPLE OF LEAST EFFORT as defined in Table 16.1.

The Ashby Space

We illustrate the functioning of Ashby's law with a simple diagram we call the *Ashby Space* (Figure 16.1). On the vertical axis we place the real-world stimuli that impinge on an organism. These range in variety from low to high. A low-variety stimulus might be an image of the moon; a high-variety stimulus might be the trajectory of an insect in a swarm.[5] On the horizontal axis, we place the variety of a system's responses to the stimuli. These also range from low to high. A low-variety response to the moon-as-stimulus would simply be to stare at it, meditate, and otherwise do nothing. Here, it is the absence of a response that is adaptive. A high-variety response to the insect swarm, by contrast, might be to chase after each individual insect flying past. This could prove exhausting and time consuming. The first type of response

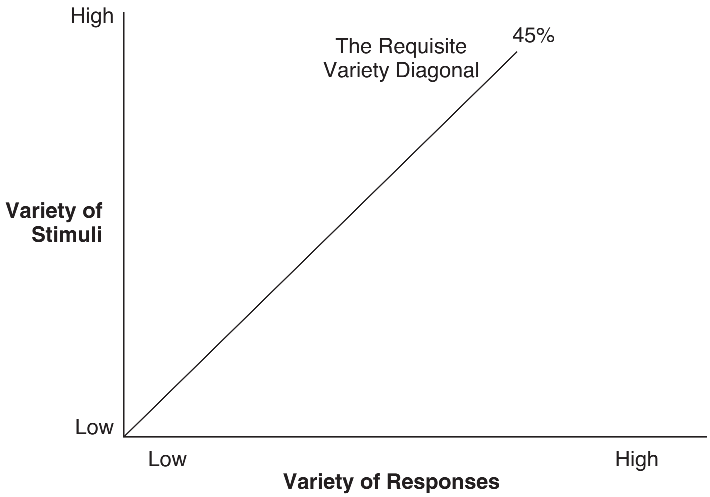

Figure 16.1 The Ashby Space

saves on scarce resources of energy and time; the second wastes them. The diagonal in the diagram indicates the set of points at which variety can be considered 'requisite', that is, where the variety of a system's response matches that of incoming stimuli in an adaptive way – it facilitates survival whether or not it does so with an efficient use of resources.

Ashby stressed the need to reduce the flow of some forms of variety from the external environment to certain essential processes in a living system. This was the role of regulation, and, as Ashby pointed out, the amount of regulation that can be achieved is bounded by the amount of information that can be transmitted and processed by a system (Ashby, 1956). The variety that the system then has to respond to depends in part on its internal schema development and transmission capacities and in part on the operation of tuneable filters, controlled by the system's cognitive apparatus, and used by the system to separate out regularities from noise (Clark, 1997) – i.e. Gell-Mann's effective complexity from its crude complexity. The more intelligent a system, the higher will be the cognitive component in its response relative to the purely behavioural one. Birds mostly act according to genetically derived behavioural instincts; monkeys produce both behavioural and cognitive responses; humans exhibit higher-level cognitive skills. There is, thus, a trade-off between the behavioural and the cognitive resources that a living system has to marshal to be adaptive.

The matching of stimulus and response variety on the diagonal can only be considered functionally adaptive, however, if it occurs inside the region of the schematic diagram labelled ***OAB*** in Figure 16.2 which describes a response budget available to a living system defined in terms of energetic, temporal and spatial resources. The curve ***AB*** constitutes the system's *adaptive frontier*, i.e. the region in which it reaches the limit of the budget it can draw on for the purposes of adaptation. To the right of this region, the mix of cognitive and behavioural variety required to respond to incoming stimuli is too high for adaptive purposes, causing the system to spend too much of its resource budget and, thus, eventually leading to its physical disintegration. Above this region, the resources consumed by the data processing required to register incoming stimuli, to interpret them, and to formulate adaptive responses also exceed the system's resource budget, eventually leading to errors and to adaptive failure – in the language of decision theory, the system's rationality is 'bounded' (Simon, 1947).

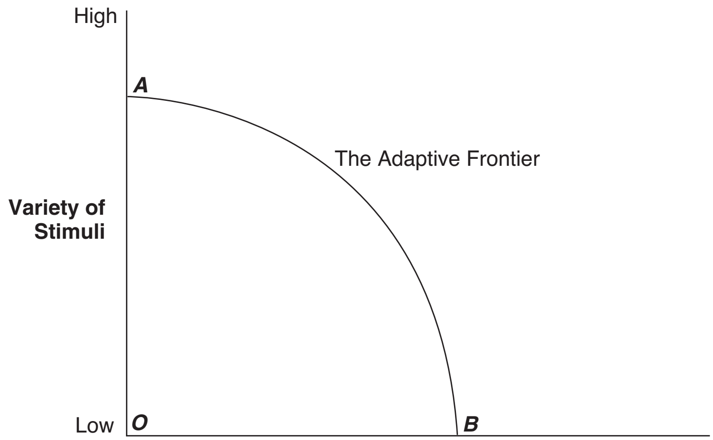

Figure 16.2 The adaptive frontier

Cognitive and physical disintegration, however, are not mutually exclusive alternatives: the first will sooner or later lead to the second and vice versa. And even when it is operating within its resource budget, at any point above the diagonal of Figure 16.1, the system is still under-adapting – cognitively or behaviourally – relative to what is actually required. Likewise, at any point below the diagonal it is using up its budget wastefully or ineffectively relative to what is required (Thaler, 1992). The challenge for an adaptive system, then, is to locate itself at some point on the diagonal in Figure 16.1 while remaining within the budget area ***OAB*** in Figure 16.2.

The shape of the resource budget, schematically represented by the curve ***OAB*** varies with the intelligence of the system. Figure 16.3 illustrates the point by comparing the resource budget of a human being with that of a hummingbird. Given its larger brain size, a human being can readily apply its resource budget to the data processing and transmission tasks that convert high-variety stimuli into low-variety ones, or vice versa. It does this by *interpreting* the stimulus, distinguishing which part of the variety associated with it is information bearing and which part is noise. In doing so, it can use its resource budget to move either down or up the vertical dimension of the Ashby Space. Hummingbirds, by contrast are better off deploying their 'flatter' resource budgets towards the right in Figure 16.3, i.e. towards more energetic responses. But human beings go further. As indicated in Figure 16.4, their capacity for social collaboration and for creating technological artefacts extends their resource budget along both the vertical and the horizontal axis of the diagram, thus significantly increasing the level of environmental variety that they can adapt to. We no longer just walk, we can fly at several times the speed of sound. And the stimuli that we process and respond to no longer originate in our immediate environment; CNN collects them from around the globe. The human case thus calls for a more dynamic formulation of Ashby's law: *The rate at which a human system's adaptation budget increases variety – i.e. at which the adaptive frontier expands – must at least match the rate at which environmental variety increases.*

What are the different response strategies available to intelligent agents in the face of variety? Consider an agent located at point ***Q*** in Figure 16.5 corresponding to some prior background activity shown as level *X* along the horizontal axis. The agent now registers a high-variety stimulus at point *Y* along the

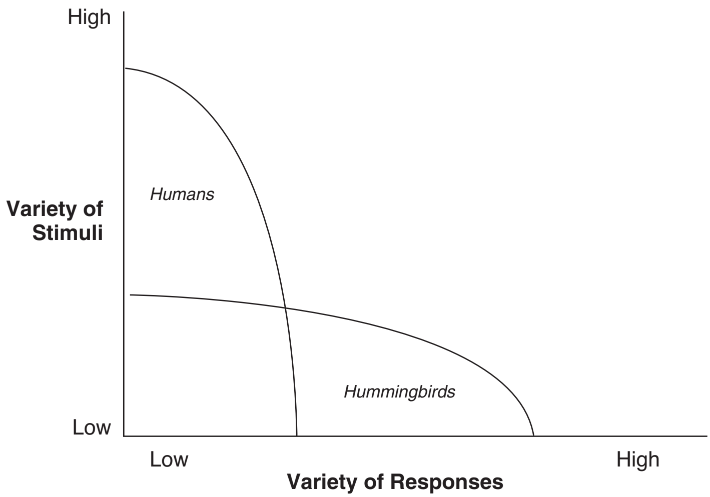

Figure 16.3 The adaptive frontier of hummingbirds and humans

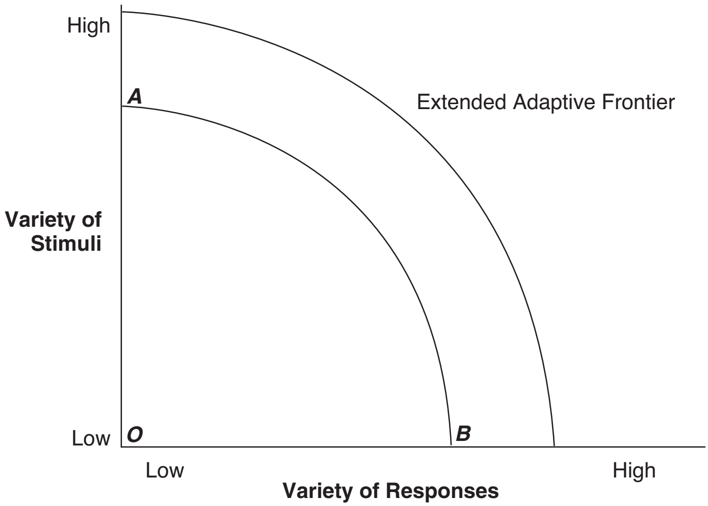

Figure 16.4 The socio-technical expansion of the adaptive frontier

vertical axis. It could respond to the variety associated with point *Y* directly in a 'mindless' behaviourist fashion either by waiting to see what happens, or by generating responses that move it horizontally to the right by trial and error until it hits the diagonal at ***C*** – i.e. one of the responses proves to be adaptive. No cognitively-driven simplification of the stimulus is involved here; its response – a mixture of cognition and behaviour – is thus costly in terms of resources consumed. In adopting this *headless chicken response*, however, the agent might well move outside its budget area ***OAB*** in Figure 16.2 thus depleting its resource budget. When the sheer variety of the stimuli allows neither prediction nor anticipation – the first specifies with precision some future event whereas the second can only orient to general classes of events – the agent would then do better to adopt the *wait-and-see* option and let nature show its hand. Alternatively, if the agent

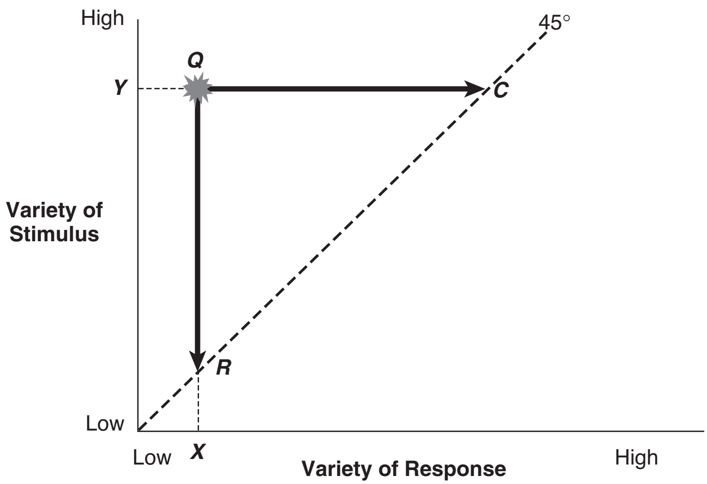

Figure 16.5 An agent at point *Q* in the Ashby space

believes that the variety of stimuli conceals some structure, it could attempt to respond in a purely cognitive fashion by moving vertically down the diagram until it approaches the horizontal axis at point ***R***. In this case, the agent treats *all* incoming stimuli either as familiar regularities or as noise and thus not in need of any *new* response. This is the strategy of agents who have 'seen it all before' and – possibly overconfidently – feel no need to actually *do* anything different. Call this a *routinizing response*. But since any downward movement calls for an interpretation and classification of incoming stimuli, whether this strategy is adaptive or not will depend on how well the resulting schema matches the real-world variety-reducing regularities confronting the agent – i.e. how *effectively complex* they are.

Intelligent adaptive agents are best off locating on the diagonal in the Ashby Space, somewhere between ***O*** and a point before which the diagonal of Figure 16.1 would intersect the budget line ***AB*** of Figure 16.2. That is, an intelligent agent first needs to *interpret* the stimuli impinging upon it. This requires a cognitive move either up or down the diagram's vertical scale that extracts information about relevant regularities from noisy incoming stimuli. The agent then needs to develop a relevant schema and respond with some *action* to regularities so extracted – a behavioural move horizontally across the diagram towards the right that is only adaptive if it stops when it meets the diagonal and does so before exhausting its budget. A cognitive move up the Ashby Space, effectively expands the range and variety of stimuli that an agent will need to process before responding – as a result, as Gell-Mann would put it, its schemas will become more complex. Such an upward move delivers *exploratory learning* (Holland, 1975; March, 1991). A cognitive move down the Ashby Space, by contrast, draws on prior learning to reduce both the range and variety of stimuli and simplify the schemas required – it delivers *exploitative learning* (Holland, 1975; March, 1991). Clearly, the further down towards ***O*** an intelligent agent can move before having to turn right and respond with a physical (behavioural) action, the more easily it can secure a quiet life for itself by achieving adaptation within its resource budget. Conversely, the further up the vertical scale towards ***A*** the rightward move occurs, the more turbulent life becomes for the agent and the more resources it has to expend in order to adapt.

The trajectory of any living system (i.e. agent) through the Ashby Space reflects its 'intelligence' – its capacity to discern meaningful regularities, develop adaptive schemas, and generate effectively complex responses. Given the limited number of stimuli that a hummingbird's brain can 'make sense' of, for example, any trade-off that the bird is required to make between its energy and data-processing resources favours drawing predominantly on its energy resources. The variety of stimuli that a human being can respond to adaptively, by contrast, is much greater so that the trade-off favours drawing predominantly on its data-processing resources. A living system's trajectory through the space thus also tells us something about its physiology. Not only are there *physiological* limits as to what may count as a stimulus, and hence as data, for a given type of system – a frog, for instance, can only detect and process peripheral movement (Lettvin et al., 1959) and a bat's movements are guided by sound, not sight – but there are also *cognitive* limits on the system's capacity to process the data contained in the stimulus. It thus confronts a problem of bounded rationality (Simon, 1986). Above the budget line the variety of stimuli may be such that a system cannot even register them. Yet, as indicated by Figure 16.4, for many living systems and especially for human beings, the budget area ***OAB*** is constantly being expanded outward from the origin by means of artefacts (Clark, 1997), cultural transmission (Gregory, 1981; Boyd and Richerson, 1985) and organized collective action (Corning, 2003). These simultaneously increase the variety of interpretive schemas available to a system on the vertical axis and that of the responses available to it on the horizontal one – its effective complexity – and thus its adaptive capacity.[6]

Complexity in the Ashby Space – three ontological regimes

Computational theory teaches us that problems whose size grows much faster than their inputs may require what effectively amounts to an infinite amount of data processing for their solution (Chaitin, 1974; Sipser, 1997). This will happen when the inputs – which here we take to be stimuli – cannot be made sense of. From the computational perspective, an intelligent agent grappling with such vast problems will then experience input stimuli as being unfathomably complex. No regularities or structure can be extracted from them and no sense can, therefore, be made of them. Even problems whose size only grows moderately faster than their inputs will be experienced as very complex to an intelligent agent. Only problems whose size is in some linear relationship with their inputs will come across as ordered. If we now take variety to be the phenomenological manifestation of complexity at work and further assume that problem-input size correlates with stimulus variety for an intelligent agent such as a human being (Grünwald et al., 2005), we can map the different input sizes of various threats and opportunities to which an agent has to adapt onto the vertical axis of Figure 16.1 to give us three distinct *ontological regimes*: the *Chaotic*, the *Complex*, and the *Ordered*. We show these in Figure 16.6.[7]

Mixing two regularities

Stimuli appearing in the *chaotic regime*[8] at the top of the diagram are hard to extract useful information from and may be judged computationally intractable, not just because of the size problem but because they are also experienced as chaotic. Unless luck intervenes, an intelligent agent drawing on conventional representations and unaware of chaos dynamics can typically make no sense of such stimuli within an adaptive time frame – i.e. before depleting its energy budget. Here, phenomena cannot even be anticipated, let alone predicted. As suggested earlier, an intelligent agent must then either wait for nature to show its hand in order to respond or it must proceed by trial and error. How it will experience the *adaptive tension* that it confronts under either option will be a function of the resources available

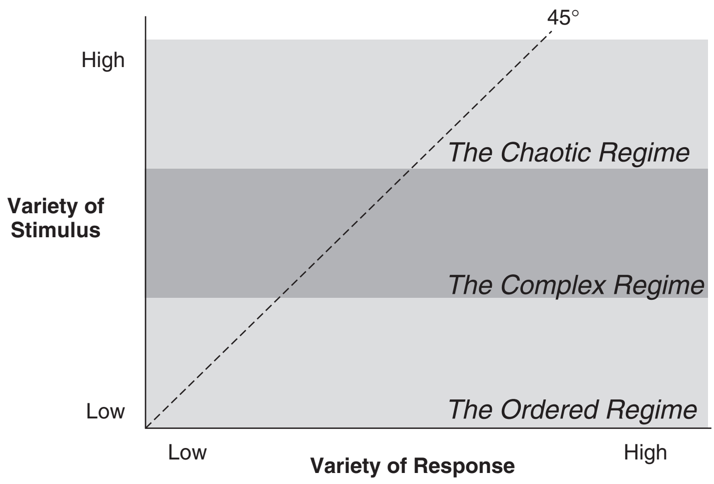

Figure 16.6 Ashby's law in three regimes

to it since a lack of resource can itself be a source of tension.

Stimuli appearing in the *ordered regime* at the bottom of the diagram, by contrast, are mostly linear in nature and are experienced as relatively unproblematic by an intelligent agent – the resulting linear regularities and noise are the stuff of everyday experience and in the human case, the products of 'normal science' (Kuhn, 1962).

In his discussion of the processes that underpin the three regimes, Gell-Mann (2002; Maguire, this volume) distinguishes between regularities produced by two fundamentally different *generative processes* (Bhaskar, 1975):

Type 1. *Reductionist Regularities:* The causal processes that are well captured through reductionist normal science, which are predictable and easily represented by equations; the focus of classical physics and neoclassical economics (Gell-Mann, 2002: 19). These characterize the Ordered Regime. They may be confidently schematized to yield predictions that then become the basis of prescriptive solutions.

Type 2. *Scale-free Regularities:* Outcomes resulting from an accumulation of random tiny initiating events amplified by positive feedback effects that generate unpredictable, seldom repeated nonlinear – and possibly extreme – outcomes that have lasting effects; what Gell-Mann calls *frozen accidents* (2002: 20). Scale-free regularities are at best problematic and beyond the reach of the explanatory traditions of normal science.

Stimuli appearing in the *complex regime* of Figure 16.2 are experienced as a blend of Gell-Mann's two types of regularities – a partly law-like and partly unpredictable mix of tiny initiating events (TIEs), frozen accidents, and power-law phenomena bathed in noise. Schema development in this regime is challenging to be sure, but computationally tractable once methods for separating out the two kinds of regularities from noise are available.

The more phenomena intelligent agents can classify unproblematically as ordered, the more they can economize on scarce data processing and energetic resources, holding these in reserve for more challenging phenomena – i.e. in responding, they will attempt to minimize the distance that they have to travel up and to the right in Figure 16.1. Human beings have a historically validated interest in steering phenomena downward in the figure towards the ordered regime if they possibly can, in order to economize on the resources needed to respond – this is the origin of their preference for simple mechanical representations identified in the opening section and, of course, of Gell-Mann's reductionist regularities. But they can overdo it. If too many of their 'interpreted' experiences end up in the ordered regime – i.e. if they all 'make sense' and can be taken for granted – human beings lose their sense of the essentially contingent nature of things and either maladapt or fossilize. When human organizations overdo it, they encounter Miller's (1990) *Icarus Paradox*, and unwittingly end up placing themselves in situations that turn out to be beyond their capacity to adapt to – e.g. they become so good at being efficient they lose their capacity to change.

Clearly, the first step in schema development with respect to some impinging real-world phenomenon is to identify the ontology appropriate for dealing with it. We outline three possibilities in Figure 16.7. If, for example, an agent interprets a phenomenon as being ordered, it will pursue the cognitively-routinizing response. This puts the agent on the least-cost trajectory of moving down the ***Q***-to-***R*** path in Figure 16.5 so as to stay within its budget area ***OAB*** – i.e. the data-information-schema-development process underlying the regularities is well understood. If, by contrast, the agent views the phenomenon as chaotic, it will either do nothing and wait or pursue the largely behavioural headless chicken response of moving from ***Q*** to ***C*** in Figure 16.5 – i.e. it could quite possibly move outside its budget area. On this trajectory the agent, knowing nothing of scalability, power laws, and scale-free theories, cannot make sense of anything. Latent regularities completely escape it, leading it to respond mindlessly. It may then expend so much undirected energy that it ends up disintegrating outside its budget area.

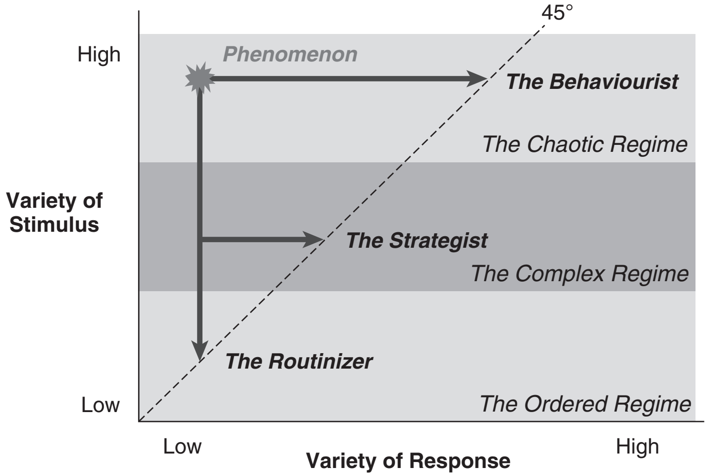

Figure 16.7 Three responses in three regimes

If an agent takes the phenomenon to be complex – i.e. neither so ordered that it can mobilize a least-cost response, nor so chaotic that it can mobilize no meaningful schema at all – it is on a scalability trajectory, one defined both by butterfly-events, frozen accidents, and nonlinearities as well as by many other attributes characterizing the Complex Regime. Here an adaptive response is feasible but more expensive than in the Ordered Regime since schema development combines both law-like *and* scalable TIEs. However, the agent can now more successfully move up the diagonal and still remain within its budget frontier.

Which ontology is adaptive for an agent may depend on how it experiences the level of adaptive tension that it confronts. Increasing tension often increases the level and strength of connectivity between hitherto unconnected phenomena, thus transforming what would ordinarily appear to be reductionist regularities into scale-free ones. TIEs will then propagate more rapidly and easily through a system, getting amplified in the process to produce magnified, nonlinear, and possibly extreme, outcomes. To illustrate: imagine a fishing net lying loosely crumpled up in a pile. Cut the net between any two nodes and the rest of the net will remain undisturbed and the effects of the cut will remain strictly local. Now place the net under tension by stretching it taut. If the net is taut enough, then a single cut could initiate a tear that would instantaneously spread from one end of the net to the other. A similar dynamic underlies the power blackouts that occasionally afflict the New England power grid when the utilities, by temporarily shutting down one overloaded station, trigger a cascade of further shutdowns throughout the North East US. Given tension plus connectivity, then, what starts off as a TIE can rapidly propagate throughout any network, growing in severity as it does so, with an extreme outcome the result. An adaptive strategy in the Complexity Regime of the Ashby Space thus needs a data-processing epistemology appropriate to the ontology underpinning the scale-free regularities that it is called upon to deal with.

Anticipating scalability – the TIEs that bind

The focus on negative feedback and equilibrium that has characterized the 'object' view of organization and much economic thinking delivers predictability, control and the maintenance of organizational identity – i.e. survival – at a low cost. After all, equilibrium spells stability and stability, in turn, maintains identity and facilitates prediction and control. Positive feedback, by contrast favours emergent self-organizing outcomes that might be anticipated *but cannot be* predicted. New order suddenly appears, often at the expense of the old order – a complexity interpretation of Schumpeter's (1934) creative destruction – but no one can tell where or when it will happen. The adaptive challenge is to anticipate it and to recognize and reinforce or negate it – i.e. to manage it – when it appears. *This, however, turns out to be less a question of how to anticipate the downstream processes of emergent self-organization than of how to anticipate the upstream scalability dynamics that drive these*. Recall that two key elements giving rise to self-organization are adaptive tension and connectivity. Positive feedback between elements connected under tension is one source of scalability that may push some TIEs to scale up – possibly to deliver extreme outcomes – but there are others. In Table 16.1 we list six that Andriani and McKelvey (2009) suggest readily apply to organizations. For example:

- *Hierarchical modularity*: Drug and toy companies having products produced in the Chinese hinterland have discovered that too much local (modular) autonomy due to culture, language, distance, time zones, cheating on product standards, trying to cut production costs, coupled with the long-distance-based costs of exerting more hierarchical monitoring (i.e. increasing connection costs) led to poisonous products. They paid a high price for modularity bordering on anarchy. Walmart has abandoned some large merger attempts in foreign countries because the connection costs of trying to get firms in foreign culture to behave like US Walmart stores were too expensive, even unworkable. Hence Simon's (1962) call for *near decomposability*, but not anarchy and Gell-Mann's (1994) *effective complexity* – just the right number of connections.
- *Combination theory*: It is like the 'perfect storm': A container ship is loaded top-heavy; a severe storm hits; the engine stalls for some unknown reason; the ship can't be steered 'into the storm'; consequently it capsizes. If any deviation occurs by itself, nothing happens. But all three together produce the extreme event.
- *Least effort*: For Zipf and his analyses of language, it was all about efficiency – I don't want to use words you don't know; you don't want to learn words I am not going to use. Over the past decades even unabridged dictionaries have shrunk in number of words – go to your library and check it out! Dahui et al. (2005) show that Zipf's Law of least effort applies only to changing language; Ishikawa (2006) and Podobnik et al. (2006) show that it only applies to industries and economies in transition as opposed to static ones. But further analysis of Zanini's (2008) industries (Drayton, 2010) shows that the power-law line of *market capitalization* is straightest in the most mature industries, insurance and machinery; see Figure 16.8. This appears opposite to what Dahui et al., Ishikawa, and Podobnik et al., find. It suggests that in free-market-based economies, market capitalization (i.e. stock-market prices) trends towards maximum 'least-effort' efficiency as traders buy and sell on information based on 'fundamentals' (i.e. valid information about the true value of the well understood mature firms); this, then, leads to the improved power-law signatures.
- *Preferential attachment*: With the 'hub and spoke' airport design, the more flights arriving at an airport, the higher the incentive for other flights to depart from there; the more flights departing from there, the more incentive for more flights to land there – the air transport equivalent of 'the rich get richer'.
- *Spontaneous order creation*: In Wikipedia, for example, one person writes a controversial entry. Others join in to expand, correct, add references, etc. Controversy, instability, and constant revising of what some other person writes emerge. The Wiki 'hierarchy', which has also emerged over the years, begins to exert a stronger 'review' role, hoping for abduction to the best explanation and stability as well.
- *Self-organized criticality*: Unlike the firms frozen in states of efficiency producing obsolete products—described in Danny Miller's *Icarus Paradox* book—effective firms have to keep changing their product lines to keep up with changing technologies and customer tastes. Perhaps we see this most obviously in hamburger stands around the world; they are pretty good at adapting to changing local tastes and to what competing hamburger chains are offering.

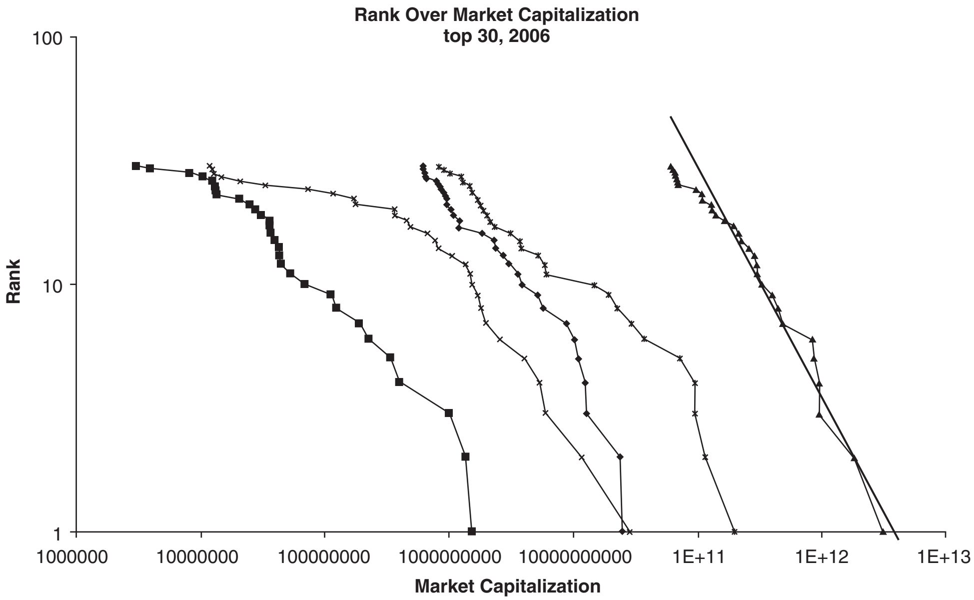

Figure 16.8 Zanini's industry market capitalizations in power-law form
Left to right, plots are of software, chemicals, machinery biotech R&D, and insurance.

Given the complex interactions involved, one cannot predict scalable outcomes. Nevertheless, an understanding of adaptive tension and connectivity allows one to rationally anticipate and adapt to the dynamics of scalability. Spotting meaningful TIEs then becomes easier since one knows what to look for. The greater the familiarity of scholars and practitioners with scalability dynamics, the earlier they are likely to spot and respond adaptively to meaningful TIEs. This will allow them to competently engage with the

Table 16.1 A sample of scale-free theories of nature*

1	*Hierarchical modularity*: As number of employees, *n*, in a firm increases, connectivity could increase by up to *n*(*n*–1)/2, producing an imbalance between the gains from more employees vs. the cost of maintaining connectivity; consequently organizations form modular designs so as to reduce the cost of connectivity; Simon argued that adaptive advantage goes to 'nearly decomposable' subsystems (Simon, 1962).
2	*Combination theory*: The interactive combination of multiple exponential or lognormal (or other skew) distributions or increased complexity of components (subtasks, processes) results in a power law distribution (West and Deering, 1995; Newman, 2005).
3	*Least effort*: Word frequency is a function of ease of usage by both speaker and listener; this gives rise to Zipf's (power) Law; the efficiency of least effort is now found to apply to changing language as well as firms and economies in transition (Zipf, 1949; Dahui et al., 2005; Ishikawa, 2006; Podobnik et al., 2006).
4	*Preferential attachment*: Given newly arriving agents into a system, larger nodes with an enhanced propensity to attract agents will become disproportionately even larger (Barabási, 2002).
5	*Spontaneous order creation*: Heterogeneous agents seeking out other agents to copy/learn from so as to improve fitness generate networks; given positive feedback, some networks become groups, some groups become larger groups and hierarchies (Holland, 1995; Kauffman, 1993).
6	*Self-organized criticality*: Under constant tension of some kind (gravity, ecological balance), some systems reach a critical state where they maintain stasis by preservative behaviours – such as Bak's small to large sandpile avalanches – which vary in size of effect according to a power law (Bak, 1996).

*We list six out of fifteen scale-free theories discussed by Andriani and McKelvey (2009).

Complexity Regime in the Ashby Space instead of escaping prematurely either into the Chaotic or the Ordered Regime.

DISCUSSION

Wiener's 1948 book on cybernetics was about control in animals and machines. Bertalanffy's 1968 book on general systems theory also framed systems in terms of top-down control processes: as in thermostats, negative feedback loops keep systems targeted on the objectives of their designers. Extending these authors' insights to cover human organizations, Thompson (1967) saw top management bureaucracies as top-down control devices that created machine-like working conditions for lower-level employees. Yet in the same period some organizational theorists (Burns and Stalker, 1961) discovered a bottom-up process of autonomous, organic changes emerging from below in organizations that allows them to respond flexibly and adaptively to changing environmental conditions (Lawrence and Lorsch, 1967). In sum, in the 1960s we see organization theory adopting the basic tenets of Ashby's *Law*, holding that efficacious adaptation occurs only when internal variety/complexity matches external variety/complexity. The Ashby Space invites organizational practitioners and scholars to now go one step further and to incorporate the insights of complexity theory with those of Ashby. It offers them a set of regimes – the chaotic, the complex and the ordered – that can help them to adapt intelligently and economically to the ever wider set of contingencies that confront them in a complex and globalizing world, one in which TIEs can rapidly scale up to produce extreme outcomes. But what are the limits of adaptation? Is there, for example, any limit to the expansion by human beings of their data-processing and schema-building resources – i.e. to the vertical expansion of the budget area ***OAB*** of Figure 16.2? A brief look at the 2007 liquidity crisis illustrates the issues involved.

An example

By August 2007 some 8,000 US (smaller) banks (Guerrera, 2009) accepted minimalist risk/reward positions by staying away from subprime mortgages, teaser loans, and by insisting that mortgage borrowers show proof of income and good credit. Such caution kept them firmly ensconced in the Ordered Regime of the Ashby Space. Some 12 major banks and over 100 other smaller banks, however, had adopted a risk/reward profile that increased the level of adaptive tension confronting them and tipped them over into the Complexity Regime of the Space. Their financial engineering models, derivatives, credit default swaps, securitized loan packages, etc., gave rise to risky loans amounting to some $50 trillion worldwide (Cooper, 2008; Morris, 2008; Foster and Magdoff, 2009). While these loans had appeared solid before the bursting of the US and other housing bubbles (e.g. in the UK and Spain, among others) – they became increasingly toxic over the course of the year. Yet, while many of these high-risk banks went bankrupt, the few that remained – Goldman Sachs, Morgan Stanley, Citigroup, Bank of America, and Wells Fargo – were able to exploit the Federal Reserve bailouts by engaging in merger and acquisition activity to emerge far stronger and larger than they had been. Here we see both positive and negative scalability dynamics at work, triggered by some early TIEs – the invention of derivatives in 1973 and of mortgage-backed securities *c*. 1985 (McKelvey and Yalamova, 2011; Yalamova and McKelvey, 2011b).

As indicated by Figure16.6, the Complexity Regime of the Ashby Space is sandwiched between order and chaos. The tipping point between the Ordered and Complex Regimes is often crossed by risk-induced tension – i.e. fear, greed, ambition, risk-taking, etc. – that leads to a phase transition. On the one hand, the 8,000 conservative small banks minimized their risks and remained in the Ordered Regime below the 1st critical value. They applied most of the conventional tools of risk management to achieve reductionist regularities. Given low levels of adaptive tension, they could pursue replicable and reliable routines and achieve levels of predictability that kept their response budgets under control.

On the other hand, in response to strong demands for wealth-creation and for large bonuses by both owners and senior employees, large banks pursued high-risk strategies that significantly increased the levels of adaptive tension they were exposed to. For them, fear, greed, ambition, and risk-taking increased tension to the point that a phase transition occurred. They thus found themselves in the Complexity Regime but getting ever closer to the 2nd critical value at the edge of chaos – i.e. the Chaotic Regime – as a positive feedback cycle (i.e. greed → risk-taking → more greed → more risk-taking → and so on, etc.) got amplified (Minsky, 1976, 1982; McKelvey and Yalamova, 2011).

Recent evidence from econophysics shows that stock-market traders cross a tipping point – indicated by what is termed the *Hurst exponent* – between efficient-market behaviour (Fama, 1970) and the herding behaviour (Brunnermeier, 2001; Hirshleifer and Teoh, 2003) that causes the power-law distribution of stock-market price volatilities (Alvarez-Ramirez et al., 2008; Yalamova and McKelvey, 2011a, 2011b). Herding behaviour results in the positive feedback and other scale-free dynamics, that, as Minsky (1982, 1986) and Yalamova and McKelvey (2011a, 2011b) argue, set off bubble build-ups. As greed and risk-taking push market tensions to the edge of chaos, they subsequently produce a market crash.

In the Complexity region of the Ashby Space we can expect to see increased levels of tension-induced connectivity and herding as traders and banks copy what appear to be the best trading rules/strategies at the time, given the absence of accurate information about fundamental values of firms. But eventually the variety of stimuli confronting traders and banks overpowers the seeming value of rule-based herding responses so that panicked reactions set in. We then see the collapse of herding-based, price-volatility-induced power laws as traders that are approaching the edge of chaos and the collapse of markets (Grech and Pamula, 2008) begin to jump ship. The headless chicken response now goes into full swing, and the adaptive resource budget gets squandered as the crash progresses. In the 2007 liquidity crisis, the failure of mortgage-backed loans quickly set up the conditions that gave rise to the ~$50 trillion's worth of toxic loans worldwide (Marshall, 2009).

In the Complexity Regime of the Ashby Space, power-law thinking trumps the Gaussian thinking and normal distributions on which most risk management models depend. Power law distributions show how TIEs can get amplified to generate extreme events. In this region, all that can be hoped for is anticipation, not prediction. Why, then, given the dangers, would managers and entrepreneurs ever want to operate in this space? Because, in this space, in contrast to the linear and hence calculable risk/returns associated with the Ordered Regime, TIEs can offer positive payoffs that may also be power law-distributed – i.e. being nonlinear the payoffs can be very large indeed. It is the relentless quest for extreme positive payoffs, forced on managers by corporate owners and talented employees that keeps pushing them to the Edge of Chaos (McKelvey, 2001, 2008). Scholars and practitioners who have some appreciation of the scalability dynamics in the Complex Regime of the Ashby Space stand a better chance of securing the payoffs available in this region while avoiding the dangers.

CONCLUSION

By integrating Ashby's perspective on the nature of efficacious adaptation with our growing understanding of the complexity phenomenon, the Ashby Space offers scholars and practitioners a conceptual framework for thinking through some of the more pressing problems that confront a globalizing world. What, for example, are the challenges of adapting to nonlinear changes in the climate?

Or of adapting to the emergence of asymmetric threats? What are the scalable opportunities that we can associate with the spread of the Internet or of mobile telephony? The above challenges will not be successfully addressed in the ordered regime of the Ashby Space. We must learn to wander out into the Complex Regime and explore what it has to offer us without necessarily falling into the Chaotic one. To succeed we need a more nuanced yet theoretically robust view of how organized systems partition their environment in their attempts to adapt to it within the resource envelope available to them. Current treatments of the human organization/environment interface are often too descriptive and too under-theorized to yield the insights needed. Much of the necessary thinking is today coming out of theoretical biology where the use of the terms 'organization' and 'environment' extends well beyond their application in management and the social sciences. The Ashby Space offers a conceptual bridge between these different disciplines. Future research – theoretical and empirical – should exploit the potential synergies on offer.

NOTES

1 Entropy measures a system's degree of disorganization, taking it to be the amount of uncertainty still remaining in the system once its observable, uncertainty-reducing regularities are accounted for.

2 Terms shown in SMALL CAPITALS are further defined in Table 16.1, with examples later in the chapter.

3 The term, *butterfly effects* dates back to the title of E.N. Lorenz's paper of (1972): 'Predictability: Does the flap of a butterfly's wings in Brazil set off a tornado in Texas?' Paper presented at the 1972 meeting of the American Association for the Advancement of Science. Washington, DC.

4 Fractals are defined as shapes that can be subdivided into parts, each of which is (at least approximately) a reduced-size copy of the whole (Mandelbrot, 1982). The same mathematical equation – or adaptive causal dynamic in biology or for firms – creates similar causal dynamics at each level of a fractal structure. See Andriani and McKelvey (this volume) for further discussion of fractals and scalability.

5 In what follows we do not distinguish between the variety that exists within a given stimulus or response vs. that which occurs across stimuli and responses. The distinction is one that the organism itself must make through acts of interpretation. See below.

6 A phylogenetic application of this argument would allow us to map the vertical and horizontal dimensions of the Ashby Space respectively onto Salthe's (1985) and Eldredge's (1985) ecological and genealogical hierarchies, yielding an evolutionary perspective on adaptation. See Brooks and Wiley (1988).

7 Although the horizontal axis could also be so partitioned, for ease of exposition we refrain from doing so.

8 Here, we are using the term 'chaotic' in its everyday sense. This is broader than its mathematical sense à la chaos theory (Guastello, 1995) since it mixes deterministic and stochastic processes.

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17

The Complexity of Industrial Ecosystems: Classification and Computational Modelling

James S. Baldwin

INTRODUCTION

Evolution is an important problem not only in terms of sustaining industry and society through adaptation and change but also, as will be highlighted in this chapter, in terms of our actual ability to perceive and make sense of what is occurring. This is because complexity and evolution are about qualitative, structural change and this poses serious problems for the classification that must underlie any attempt at modelling the situation. Although attempts have been made to incorporate evolution in the many definitions, models and case studies, typically only one side of the evolutionary story is told – that of optimization and improved performance. Evolution, however, is much more chaotic with change as the only constant. Qualitative change, as with structural and organizational transformations, directly results from the complexity of the systems involved and is, as a consequence, far harder to represent and model. However, classification and modelling techniques from the biological and physical sciences are increasingly used and evolutionary approaches in particular, that of cladistic analysis and representation, lead to classifications, models and simulations, that more accurately describe and mimic the activities in real systems. Insightful and telling applications can be made and models constructed that follow and explore the changing complex organizations and their consequent patterns of energy and materials. In addition, the human dimension representing, for example, the consequences of decisions and implementations such as policy changes, new innovations and technologies may also be explored. Evolutionary classifications and models can therefore serve as decision support tools to lessen or manage the risk and uncertainty of future evolutionary trajectories.

INDUSTRIAL ECOLOGY

The purpose of this chapter is to highlight how complex systems thinking, and the evolutionary classification and modelling tools it brings, can provide a better understanding of how different industrial system configurations have evolved. For this purpose the subject area of industrial ecology (IE), an organizing concept with which to model the transitions necessary for industry to become sustainable (Erkman, 1997), will be used as the research context. Since the seminal article of Frosch and Gallopoulos (1989) there has been much debate, many definitions and interpretations, numerous models ranging from the simple to the complex, various case studies of industrial ecosystems and symbioses, and countless tools. However, as with all new disciplines, there are several areas of ambiguity and inconsistency and, as such, many areas of further research and refinement. One specific area, analysed under the light of an evolutionary framework, is the notion of evolution in IE, particularly with definitions, classifications and models.

Definitions

There is no agreed standard definition that fully captures the ethos of IE and satisfies all researchers. However, there are many underlying themes common to most definitions. Frosch and Gallopoulos' (1989: 94) definition of IE is as follows:

> In such a system the consumption of energy and materials is optimized, waste generation is minimized and the effluents of one process ... serve as the raw material for another process. The industrial ecosystem would function as an analogue of biological ecosystems.

From this definition, Frosch and Gallopoulos hint that a systems perspective is required. They emphasize energy and materials as the focus and that both should be optimized. Frosch and Gallopoulos give an indication, without actually specifying, that a closed looping of materials is required, as waste is used as resources for another process. They also argue that the biological analogy is a useful way in which to understand industrial systems. Frosch and Uenohara (1994: 2) elaborated on their thinking five years later:

> Industrial Ecology provides an integrated systems approach to managing the environmental effects of using energy, materials, and capital in industrial ecosystems. To optimize resource use (and to minimize waste flows back to the environment), managers need a better understanding of the metabolism (use and transformation) of materials and energy in industrial ecosystems, better information about potential waste sources and uses, and improved mechanisms (markets, incentives, and regulatory structures) that encourage systems optimization of materials and energy use.

Although sustainable development is not specified *per se*, reducing environmental impacts as well as the optimization of resource use are the main goals. They also introduce the idea of top-down pressure in the form of markets, incentives, and regulatory structures. Graedel (1996: 70), whose work has helped enormously to establish and extend the discipline, offered a similar definition:

> Industrial ecology is the study of the means by which humanity can deliberately and rationally approach and maintain a desirable carrying capacity, given continued economic, cultural, and technological evolution. The concept requires that an industrial system be viewed not in isolation from its surrounding systems, but in concert with them. It is a systems view in which one seeks to optimize the total materials cycle from virgin material, to finished material, to component, to product, to obsolete product, and to ultimate disposal.

This definition, like the others, emphasizes the integration of industrial and natural systems, optimization of resource use, and evolutionary processes. In some ways it confounds two different aspects that possibly should be seen as separate. First, there is a systemic view of the flows of energy and materials that a particular industrial system actually embodies. But second, there is the issue of making this 'sustainable', reducing the overall flows and wastes, which is a goal that would only be enacted if there were a 'global' agent that actually controlled the whole system. In reality however, this is a complex system and different parts of the overall system, while being connected by flows of energy, materials and money, are usually controlled by different agents, who tend to act according to their own perceived interests. Part of the real opportunities and difficulties that affect the sustainability of the system cannot therefore be addressed without consideration of the motives and strategies of the agents and their level of knowledge. In addition, the definition includes the use of tools associated with IE, the notion of carrying capacity and the cradle to grave perspective (i.e. 'the total materials cycle'), which is the backbone of life cycle analysis. Allenby (1994: 47) argued that:

> Industrial ecology may be defined as the means by which a state of sustainable development is approached and maintained. It consists of a systems view of human economic activity and its interrelationship with fundamental biological, chemical, and physical systems with the goal of establishing and maintaining the human species at levels that can be sustained indefinitely – given continued economic, cultural and technological evolution.

This definition, although similar, is more comprehensive and has an altogether different emphasis. Like the last definition, Allenby (1994) argues that a systems perspective is required to fully understand industrial ecosystems but perhaps does not realize that it is complex systems perspective that is required – one that would recognize the probably divergent short and medium term criteria of the agents that actually make up the system. However, he also stresses that it is a means to an end, which is sustainable development. In addition, they argue that the view taken of the industrial system is both of an evolutionary nature and that an integration of industrial and natural activities is needed. Evolution is an integral aspect in the author's thinking. Allenby's (1994), definition is in the exception as he argues that if optimization was the only objective, the industrial structure would soon become rigid, uncompetitive and inevitably non-sustainable.

Classifications, typologies and taxonomies

Building on these definitions, several industrial classifications, typologies and taxonomies have been proposed not only as a means of identifying different organizational forms that exist but also, and perhaps more importantly, as a tool to both help explain and deal with change, and use as a guide for organizational re-engineering. Graedel (1996) provides the simplest and perhaps most often cited typology of Type I–III industrial ecosystem activity. By assuming that 'evolution' should proceed in a particular direction, Type I ecosystems typically are considered to represent very immature systems, at a time when space and resources are plentiful. Material flows are almost always linear – they enter the system, energy and nutrients are extracted, and the degraded materials leave as unutilized waste. However, it is assumed that as the system grows and as both space and resources become scarcer, a degree of material recycling occurs as decomposer populations begin to grow, limiting the flow and impact of waste materials. This is a Type II ecosystem. Type III ecosystems represent fully mature ecosystems where most of the available resources are actually contained in the ecosystem – virgin resources have been extracted and are virtually non-existent. This system is more or less completely cyclical. When this view is mapped onto industrial activities, Graedel (1996) argues that most industrial ecosystems are at the Type I stage with a minority achieving some resemblance of Type II. No industrial ecosystem has yet achieved Type III.

A whole series of different classification schemes have since been proposed for industrial ecologies. The main ones are: Chertow (2000), after a review of the indusrial symbiosis literature and an in-depth study of eighteen Eco-Industrial Park (EIP) candidates, developed a taxonomy distinguishing between five material exchanges; Lambert and Boons (2002: 471) proposed three Types which can be further distinguished between greenfield and brownfield sustainable industrial development initiatives; Lowe et al. (1995) provided three separate typologies in their attempt to specify exactly what an Eco-Industrial Park (EIP) is and is not.

Industrial classifications are continually developed both to map change that has occurred and to help the agents involved to change their practices to keep competitive and sustainable. To date there have been many classification schemes developed mostly by academics, production engineers and industrial systems' engineers who, although have an intimate knowledge of the systems under study, apply little from the science of classifications (McCarthy, 1995). As a consequence the classification schemes are typically subjective, have little consistency and have limited generalizability (McCarthy, 1995).

THE PROBLEM OF EVOLUTION

Historically, problems have been encountered in not sufficiently capturing evolutionary processes in industrial ecology, particularly with an over-reliance on the reductionist paradigm and the over-emphasis on pure optimization which can be seen in the various case studies that have emerged. For example, the most commonly cited example of an eco-industrial park, indeed the first industrial symbiosis to be officially recognized in academia, is the Kalundborg Industrial Symbiosis on the Danish island of Seeland (refer to the diagrammatic model shown in Figure 17.1). What is interesting about Kalundborg, like several other cited examples, is that it developed spontaneously without any external pressure (Lowe, 1997). The impetus to develop these recycling structures was purely economic – both to reduce the costs increasingly associated with waste disposal and as an extra

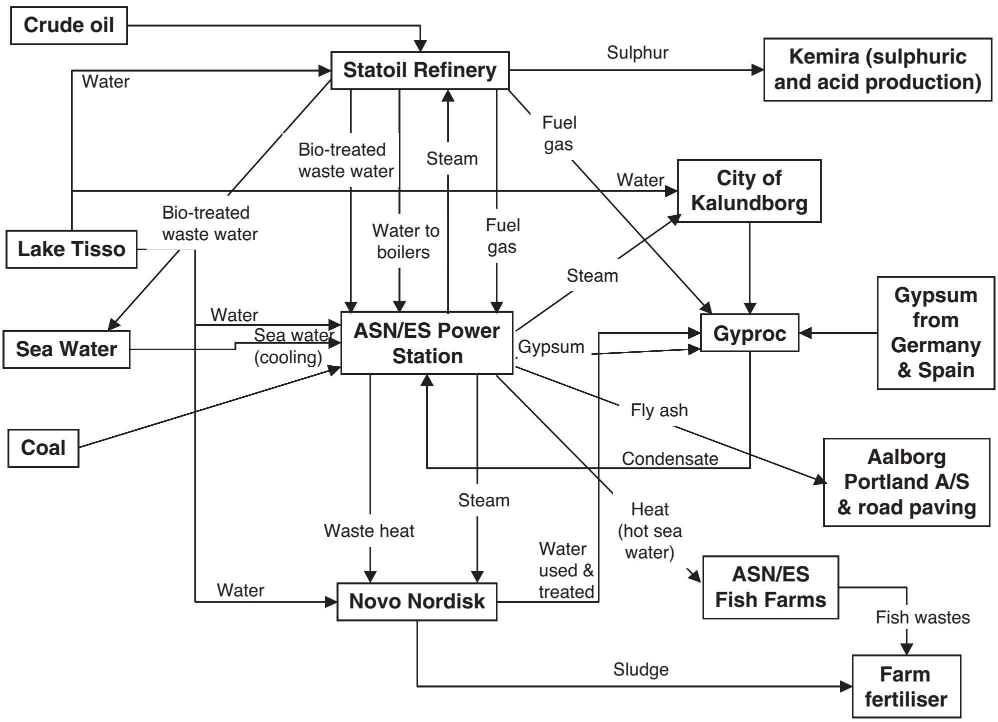

Figure 17.1 The industrial symbiosis at Kalundborg (adapted from Lowe et al., 1997)

income-producing service for other companies located nearby (Desrochers, 2002).

Frosch, Sagar and colleagues have also documented a similar industrial ecosystem relating to the metals-manufacturing industry in the American state of Massachusetts (e.g. Frosch and Gallopoulos, 1989; Frosch et al., 1997; Sagar and Frosch, 1997). It also differs somewhat from the last case study as the focus, although geographical, was more restricted to copper/copper alloys and lead. This industry was studied as metals represent a substantial fraction of industrial consumption, are unlikely to be substituted in the near future, and are involved in one of the oldest industrial systems. Tracking the materials flows from these firms led to the diagrammatic model shown in Figure 17.2.

This systems-level analysis does, however, enable a number of insightful observations. Sagar and Frosch (1997) found that the flow of materials within the individual companies demonstrated an array of complexities dependent on the different types of operations within each company – the more processing operations, the more complex the flow of materials. The flow within the system as a whole was also complex with each firm connected in, often very unique, relationships making it difficult to develop generalizations. The key to the recycling process was largely down to certain sectors, particularly scrap dealers and the secondary processors such as smelters and refiners. Sagar and Frosch (1997) also found several companies that although occupied small niches (e.g. waste agglomerators/brokers) were very significant in the facilitation of material flows around the whole system. Importantly, evolution played a significant role as the system is continually changing as some species become extinct and other species and their relationships and connections evolve. In reality though it is unclear that the ‘natural’ evolution of such a system must necessarily lead to improved overall performance and reduced waste.

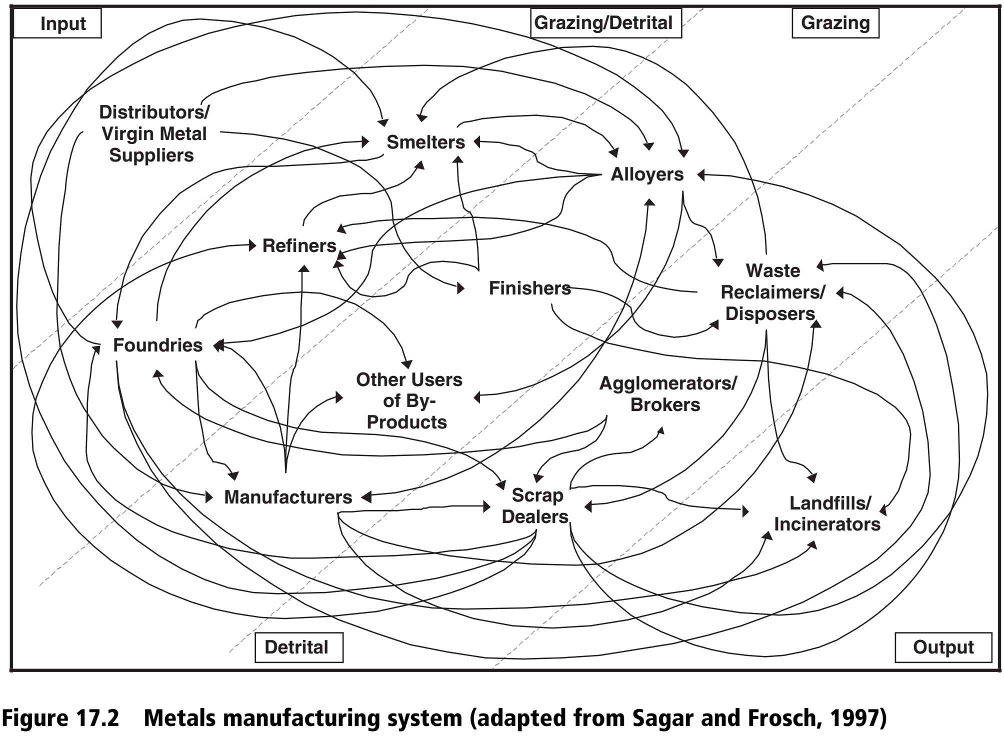

Figure 17.2 Metals manufacturing system (adapted from Sagar and Frosch, 1997)

Overall improvements would seem to require not only a systems view and some corresponding system wide governance structure.

The confusion over optimization and evolution in IE is even more evident when the typical models of IE are critically scrutinized. For example, in Graedel's (1996) somewhat simplistic view, an ideological view of ecosystem development, evolution is depicted purely as an optimization process of materials. There are also many more detailed models that hold different views and approaches as Boons and Baas (1997) highlight in their typology of the different forms of IE. These descriptive models, particularly the product and material focus, have recently been accompanied by an abundance of modelling methodologies. Most, however, are for the individual organization and as such, the tools and models are not meant to model evolution and are purely optimization techniques. However, when the boundary changes to the sectoral or geographical focus, the purpose of the modelling also changes. Typically, the models are utilized to gain insights into potential future scenarios. As such, the models not only have to consider optimization, but also evolutionary processes. One computer modelling technique, termed 'mass balancing', is gaining particular popularity (Linstead and Ekins, 2001). Mass balancing builds on the input–output models from economics, accounts for materials (and energy) that enter and leave the system, keeping in mind storage and chemicaltransformations. There are typically two approaches that are used. The first assumes a 'steady state' or 'equilibrium' system. The second approach (Duchin, 1992) is more dynamic and models the system with the flows of materials changing over time. Nonetheless many of these perspectives and modelling techniques, true to the definitions of IE, again assume that evolution must lead to optimization.

There are exceptions though. These models, however, are of a more qualitative nature, highlighting the difficulty of representing evolution in modelling. For example, Korhonen (2001) extends the IE perspective by not only focusing on the optimization process of recycling (or to use Korhonen's term 'roundput'), but also diversity, locality and gradual change – the 'four ecosystem principles for an industrial ecosystem' (see also Baldwin et al., 2004). Korhonen (2001) argues that the survival of the ecosystem is critically dependent on diversity. This diversity needs to be present at several levels of organization – in organisms, in populations of species, and at the level of the ecosystem. There also needs to be diversity in interdependencies, in relationships (e.g. co-operative structures, symbioses and mutualisms), and in information flows. Diversity creates strong flexibility and adaptability, which is essential for coping with changes in the environment. In terms of industry, Korhonen (2001) sees the optimization principle of the old mechanistic Fordist or Taylorist regimes, which leads to widespread homogeneity, as one of the main barriers to diversification and long-term survival or sustainability.

Models are concerned with first understanding but then predicting and planning for the expected trajectory of a system (Allen, 1984). Indeed, it is generally thought that the ability to predict the future state of a system is a pre-requisite of understanding. Through the classification and identification of system components, causal links and underlying mechanisms, fundamental laws of nature were thought to be understood (the Newtonian mechanical model) – the future behaviour of the system was therefore believed to be inevitable. However, new thinking and research on systems that can exchange energy and matter across their boundaries has shown this premise to be flawed. Although Newtonian models are correct for isolated systems that inevitably reach thermodynamic equilibrium, they are inappropriate when considering the activity of natural and social systems, the evolution of which pushes the system further from equilibrium. This is not to say that mechanical models are without use, they are just inappropriate for most living and meta-living systems (Allen et al., 2006a).

All models are a reduced description of what is actually there. The modeller attempts to take out the superfluous and leave only the essential elements. The typical result is a mechanical model. Most mathematical models, however, also represent change over time. This point is important, because the change that is usually contained in the model is of a purely quantitative nature. Qualitative change, such as structural change, adaptive responses and learning within, are therefore excluded. This is a huge problem when studying evolution, as qualitative change is an inherent characteristic. When qualitative change takes place in a system, the model typically needs to be at least re-calibrated, and at worst re-designed (Allen, 1992) as new variables and processes emerge and have to be taken into account.

Another problem is that modellers are usually trying to find the most optimal state – according to their particular definition – that the system can take. If we can reduce reality to a machine, then we would be able to determine whether certain modifications result in the system being faster, using less energy and materials, requiring less labour and skill and, more often than not, saving money. As we shall see, models of both sustainability and IE are not so much predictive models but are overt attempts to optimize the system towards sustainability without any real thought of evolution. This is not to say that optimization is altogether erroneous, but that it represents only one side of the evolutionary story (Allen, 1992).

Evolution is a subtle partnership of chance and determinism and the future not wholly inevitable (Allen, 1992). When a system is far from a bifurcation point, the system is deterministic, in as much as fluctuations from non-average behaviours do not perturb the average course. Average behaviours dominate and this means that decision making agents involved in the system can make sense of it and pursue their particular path of optimization. This is somewhat representative of the notion of incremental evolution and most descriptive and mechanistic models are often appropriate.

Chance plays a crucial role however, when the system, close to bifurcation, becomes unstable and may decide the next trajectory. Indeed, average behaviour (the substance of typical models) plays no role in choosing a branch; it is the non-average or eccentric behaviours, the variations around the average, that lead the 'decision' (Allen, 1984). This is more representative to the idea of punctuated equilibria (Gould and Eldridge, 1977), certainly one of successive structural instabilities. Once change has occurred, however, the averages are redefined and agents can make sense of their situation and can recommence their optimization. This sheds light on the issue and difference of prediction and post-diction. With hindsight it is easy to see how, and to some extent why change occurred, but when looking to the future, it may be one of many eccentricities that shapes the direction taken. Another important feature of evolutionary systems concerns the solutions derived. Although the equations are quantitative, the solutions (the different branches that may be taken) are qualitatively different (Allen, 1992). The causation or explanation is paradoxically circular (Allen, 1984). The learning is from within the system and models that truly represent evolutionary processes need to incorporate this.

The new thinking from the science of complex systems highlights the problems with the Kalundborg system in particular as the individual organizations are connected, in the majority of cases, by physical, hard-pipe connections. New innovations, changing technologies, new external pressures, such as legislation and public pressure, new energy sources, new materials, and mergers and takeovers could have dramatic effects on the whole system, perhaps resulting in collapse. Although perhaps unlikely, these issues do raise questions about Kalundborg's future prospects. There are two main points here both concerning modelling. The first is that the models developed in the case studies tell you something of the present whilst also giving you a glimpse of the past. The second point is that the actual Kalundborg system was guided from the beginning by an implicit model that was reductionist in nature. The model prioritized optimization of materials and energy flow, as recommended by IE, through symbiotic relationships between the companies. However, as a consequence of optimization, variety, micro-diversity, redundancy and 'slack' within the system was sacrificed. This has significantly diminished the capacity to change, to respond to external events, to experiment, and thus to evolve. This is why the system is now regarded to be highly rigid and vulnerable, and is ultimately a consequence of mechanical models (Allen, 1994).

Sagar and Frosch (1997), when comparing the Massachusetts system with the Kalundborg system (the rigidity of the hard-pipe connections and long-term agreements), argue that there appears to be far more redundancy, adaptive responsiveness, flexibility and dynamism which they argue will benefit the system in terms of adapting to changing external stimuli. This adaptive responsiveness, they argue, is the result of diffuseness over a large geographical area. However, when taking the example of the Massachusetts system, the problem is somewhat different. The first difference is that this system happened spontaneously without any model for guidance and was later 'discovered' then modelled. Without the guiding model, the system is arguably far more fluid, there is far more diversity and thus redundancy, giving the system far more flexibility and adaptive capability. The danger now is that there is a model available, albeit descriptive and diagrammatical, giving the modeller and IE practitioners far more incentive to begin optimizing. When looking at the Massachusetts system, the model still suffers the same problems as the Kalundborg system in that although being a good description of the present with glimpses of the past, there is no indication of what may happen in the future. The models have no capacity to change qualitatively. Clearly, models are needed that take account of real-life qualitative change that may drive the system in many possible future directions, including collapse and decline. In terms of modelling, the capacity to change and evolve is directly related to the modellers' assumptions when developing models.

To overcome the problem of evolution in both constructing classifications and modelling, recent work, which is a collaborative effort between the Universities of Sheffield and Cranfield in the UK, is beginning to show promise in providing some solutions to these problems. The project is a synthesis of disparate approaches, both of which share the common theme of evolution. One approach is manufacturing cladistics, an evolutionary classification scheme from the biological sciences, an example of which is presented in the next section. Manufacturing cladistics has been utilized to date as a best practice benchmarking classification system. The approach may also be employed as a tool for organizations to locate their position in evolution with respect to their competitors providing the opportunity to re-engineer their organization (McCarthy et al., 1997; McCarthy and Ridgway, 2000). The other is evolutionary systems computational modelling, a quantitative approach from the physical sciences, presented in a later section. Evolutionary systems' modelling is an application of complex systems theory and has successfully been applied to ecosystems, urban systems, industrial networks, economics and financial markets. When these two approaches are combined a framework is created enabling both the simulation of the evolution of manufacturing form and an exploration of potentially new organizational structures.

APPLICATIONS PART A: EVOLUTIONARY CLASSIFICATIONS

As biologists study life in all its forms, taxonomy and classification have been useful tools right from the beginning of this discipline. Managing all the information on all living entities, their genetics, form and behaviour, has been immensely helped through these techniques and as such the methodology has been refined to an extent that they are now integral aspects of biology. Evolution is central to the main classification methods. Indeed evolution and classification have helped shape understanding why an entity looks like it does and behaves in a certain way. One of the first questions asked by classification researchers is (e.g. Good, 1965; McCarthy et al., 2000): why construct a classification in the first place? Good (1965) suggested four purposes: (a) for mental clarification and communication; (b) for discovering new fields of research; (c) for planning an organizational structure or machine; and (d) as a checklist. Similarly, Haas et al. (1966) argued that there were four advantages, i.e. that a realistic classification could: (a) refine hypotheses; (b) determine validity and utility based on logical and intuitive reasoning; (c) provide a basis for prediction; and (d) specify populations from which samples could be drawn.

In classification science there are two main biological principles – phenetics and phylogenetics. Phenetics investigates the similarities between objects/entities and ignores or dismisses the potential evolutionary link, i.e. entities sharing a physical similarity are grouped and entities having physical differences sorted into separate groups (Ridley, 1993). Any physicality may be used, for example, bones, limbs, colour, etc. Phylogenetics, on the other hand, is based on evolution and ancestral commonality – similarities in physical form is consequential (Ridley, 1993). The classification process produces a hierarchy of branches commonly known as the 'evolutionary tree'. Fitch (1984) argues that cladistics is the identification of evolutionary links between taxa. The word 'cladistics' is a derivative of the Greek term 'klados' meaning branch and was developed by Hennig (1950) while working on phylogenetic classifications. Data is typically drawn from surviving taxa. This approach investigates the evolutionary links between entities and studies common ancestors. Two species may be placed in the same group if they share a recent ancestor, whereas they may be placed in different groups (but still the same family) if the ancestor is more distant. The more evolutionary distance between the entities then the further apart their respective positioning in the classification (see Figure 17.3).

Ridley (1993) after reviewing the different classification schools, i.e. phenetic, cladistics and general evolutionary classification disciplines, to assess their ability to construct natural and objective classifications (rather than artificial and subjective classifications), concluded that only cladistics could fully satisfy these criteria. Using evolution as an external reference point (evolutionary history cannot be changed) classifications will be unique and unambiguous.

Returning to the question: why construct a classification in the first place? One of the answers provided by Good (1965: 33) was 'for planning an organizational structure or machine'. This was one of the main drivers for developing manufacturing cladistics. When classifications are applied to manufacturing and industry, the pioneers of this approach, McCarthy et al. (2000: 78), argue that a classification 'would facilitate the storage, alignment and development of structural models of manufacturing systems [that] . . . would provide researchers and consultants with a generic library of structural solutions for enabling manufacturing systems to maximize their operating effectiveness'. That is, if a cladogram were constructed comprehensively enough it would provide a blueprint with which industrialists could use as a guide to help to change their structure to gain competitive advantage.

During the last decade research in manufacturing cladistics has accumulated rapidly. The approach, which concentrates on the evolution of physical attributes, appears to be the most productive for classifying manufacturing types and for offering guidelines for change initiatives (e.g. McCarthy et al., 1997, 2000; Leseure, 2000). The manufacturing cladistic approach is not an entirely new approach and has to date been applied to

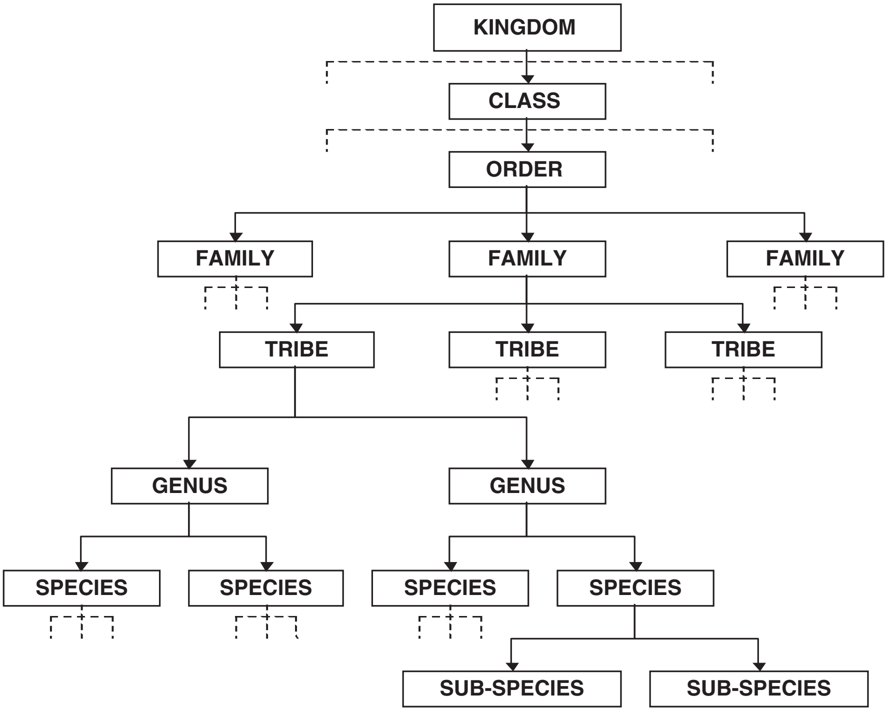

Figure 17.3 A taxonomic hierarchy presented dendrogrammatically (McCarthy, 1995)

a complexity of manufacturing organizations (McCarthy, 1995), to commercial aerospace supply chains (Rose-Anderssen et al., 2009a), the hand-tool industry (Leseure, 2000) and the automotive industry (McCarthy et al., 1997, 2000). Similarly, when applying this approach to industrial ecosystems it is possible to generate phylogenetic hypotheses and then begin to re-construct the evolutionary unfolding of the different industrial ecosystem configurations.

Evolving industrial ecosystems: a classification

In line with basic steps in constructing an industrial cladistic classification, the methodological approach adopted for the construction of a conceptual cladogram centred on the collection of data from secondary sources. Two types of data sources were collected from the literature and world-wide-web. The first type concerned general evolutionary characteristics of both natural and industrial ecosystems. The second type of data source provides the foundation for the phylogenetic hypotheses and was based on both (a) typologies already proposed in the literature, and (b) theoretical discussions of what constitutes an industrial ecosystem, industrial symbiosis, eco-industrial network, and eco-industrial park. Additional industrial ecosystem forms and their characteristics were identified through reviewing the case study literature concerning (a) industrial symbioses, (b) eco-industrial networks, and (c) eco-industrial parks. The aim of combining general evolutionary characteristics with industrial ecosystem typologies and characteristics was to produce phylogenetic hypotheses from the industrial literature and position them diagrammatically in terms of evolutionary or successional maturation (using Graedel's (1996) Type I–III system for ease of reference). Forty-three distinct industrial ecosystems were identified

Table 17.1 Forty-three distinct industrial ecosystems

Park Organizations		*Complex/Cluster Organizations*	*Network Organizations*
1. Local craft industry supply system	12. Energy efficiency PPS 13. Waste to energy park	25. Primitive cluster/ complexes	33. Primitive supplier network
2. IR local supplier system	14. Renewable energy PPS 15. Multi-theme EIP Stage 1	26. Heavy process industrial zone	34. Rudimentary EIN 35. Generalized EIN
3. Mixed parks (SMEs)	16. Multi-theme EIP Stage 2	27. S-BPX	36. Between firms GEIN
4. Benign park	17. Multi-theme EIP Stage 3	28. M-BPX	37. Within firms GEIN
5. Green powered park	18. Petrochemical park	29. M-BPX+EC	38. RRN
6. Water treatment park	19. Petrochemical symbiosis	30. Themed technology cluster	39. IRRN
7. IRRP	20. Green petrochemical EIP		40. IRRN+EC
8. IRRP+EC	21. Intensive agro-industry	31. Green products cluster	41. Specialized EIN
9. Supplier park	22. Agro-EIP	32. Environmental technology cluster	42. Green products network
10. Power plant parks	23. Integrated Agro-EIP		43. Environmental technology network
11. Power plant symbiosis	24. Integrated Social Agro-EIP		

(Table 17.1) representing a spatial divergence of forms, namely parks, complex/clusters and networks.

It must be emphasized at this point that this list of different industrial ecosystems is far from exhaustive, but what was considered generic forms of industrial ecosystems. In addition, there are several forms that do not even exist but represent idealized forms of industrial ecosystems. Sixty-five characteristics or character-states (CSs) were also identified in the literature. These are listed in Table 17.2.

CSs have a twofold purpose: to describe and to distinguish between organizational forms, i.e. they have evolutionary significance. Again, this list is far from exhaustive. Figure 17.4 shows the full cladogram of the 43 industrial ecosystems.

Figure 17.4 is the conceptual cladogram that was developed through the research and describes the evolutionary history of EIPs. All industrial ecosystems in the evolutionary history share the characteristic of product material trade (CS1). The first recognizable industrial ecosystem is referred to as the Local Craft Industry Supply System and consists of a material trade based on limited availability (CS2). During the industrial revolution as the product material trade system becomes more organized (CS3) the IR Local Supplier System emerges and prospers. From this simple industrial system, it is argued that three spatially distinct industrial organizational forms evolve: parks, clusters/complexes and networks.

At this stage, the cladogram would offer actors/observers, whether they are the industrialists and manufacturers involved, the local community or government officials, a benchmark of past, current and best practice. Specific industrial ecosystems would be able to be identified in terms of their evolutionary position on the cladogram and use it to: (a) identify potential problems or pitfalls; (b) assess opportunities; and (c) for organizational re-engineering for sustainability. Policymakers and decision-makers could also utilize the cladogram in terms of, for example, attracting the right types of industries, making funding available tied in to certain types of complementary activity and/or setting the goals and scope of regional industrial activity. It would also provide assurance to society as the cladogram can be essentially used as a 'road map' to sustainable industrial development.

However, there are limitations. The cladogram is ordinarily a description of the past and is of no use to the leading or 'world-class' industrial ecologies that can only be compared with earlier and even inferior industrial ecologies (although the inclusion of futuristic and idealized forms has been attempted for the first time in this research). It also says nothing about the 'losers' (those industrial ecologies that didn't survive for one reason or another), which is perhaps an important

Table 17.2 Characteristics of industrial ecosystems

1. Product material trade
2. Material trade based on limited availability
3. Organized product material trade system
4. Co-located organization
5. Light Industrial activity
6. Diverse cross-sector collection of SMEs
7. Limited relationships with neighbours
8. Environmentally friendly construction
9. Environmentally friendly infrastructure
10. Renewable energy (solar, wind, biomass)
11. Ecological treatment
12. Wetland and lagoons
13. Common investment
14. Strong relationships between park members
15. Collection, sorting and processing firms
16. Re-use and recycling firms
17. Re-manufacturing firms
18. Disassembly firms
19. Energy cascades
20. Co-located suppliers
21. Product complexity
22. Heavy Industrial activity
23. Power generation
24. Fossil fuel consumption
25. By-product exchanges
26. Energy management firms
27. Energy technology firms
28. Municipal waste incineration
29. District heating
30. Renewable energy
31. Agro-connections – by-products and/or energy
32. Community involvement
33. Recreational facilities
34. Educational resources
35. Petrochemicals
36. Simple linear processing
37. Multi-symbiotic relationships
38. Green chemistry
39. Agricultural products
40. Industrialized agricultural practices
41. Petrochemical inputs
42. Crop exports
43. Ecological-based husbandry
44. Strengthened rural socio-economic status
45. Preservation and restoration of land and water
46. Full by-product utilization
47. Spatially diffuse
48. Locally diffuse organization
49. Location due to zoning
50. Good communication channels (waterway, train)
51. Limited by-product exchange
52. Heat recovery
53. Co-generation
54. Sector-specific cluster (e.g. electronics, textiles)
55. Green product manufacturers (e.g. lighting, appliances)
56. Environmental technology manufacturers (solar panels, wind machines)
57. Environmental technology R&D
58. Widely diffuse organization
59. Material supplies sourced regionally, nationally and globally
60. Recycling of primary materials (e.g. metals)
61. Cross-sector exchange of by-products
62. Unaware of relationships
63. Vertical by-product integration
64. Internal closed-looping or greening
65. Material specific recycling (e.g., metals)

omission. Learning from past mistakes could prevent future disaster. Furthermore, the cladogram gives no insight, with the exception of *post-hoc* analyses, into many of the problems confronting management decision-makers. Nonetheless, by combining manufacturing cladistics and evolutionary systems modelling, a quantitative approach from the physical sciences, cladograms may be constructed that include and explore not only past and present organizations but also credible industrial ecologies that could have evolved or that may evolve in the future.

APPLICATIONS PART B: EVOLUTIONARY SYSTEMS MODELLING

According to Allen (1992) a hierarchy of models can be elicited based on modelling assumptions taking the purpose of the model from prediction and certainty to exploration and potentialities. All models can be thought of as having at least two underlying assumptions. The first is that there is a boundary between the system and its environment and the second is that the components of the system can be classified leading to a taxonomy. Additional assumptions are then made pertaining to components and their interactions. Predictive models, such as system dynamic models, appear to have perfect knowledge and understanding, and assume that both components and their interactions are normally distributed about the mean; in other words, average. With only the average represented, there is just one future path – the most probable. When the modeller begins to introduce non-average interactions between system components, as with most agent-based models, more scenarios and possible trajectories are explored and the predictive capability reduces. In other words, when diversity is introduced, many types of interactions

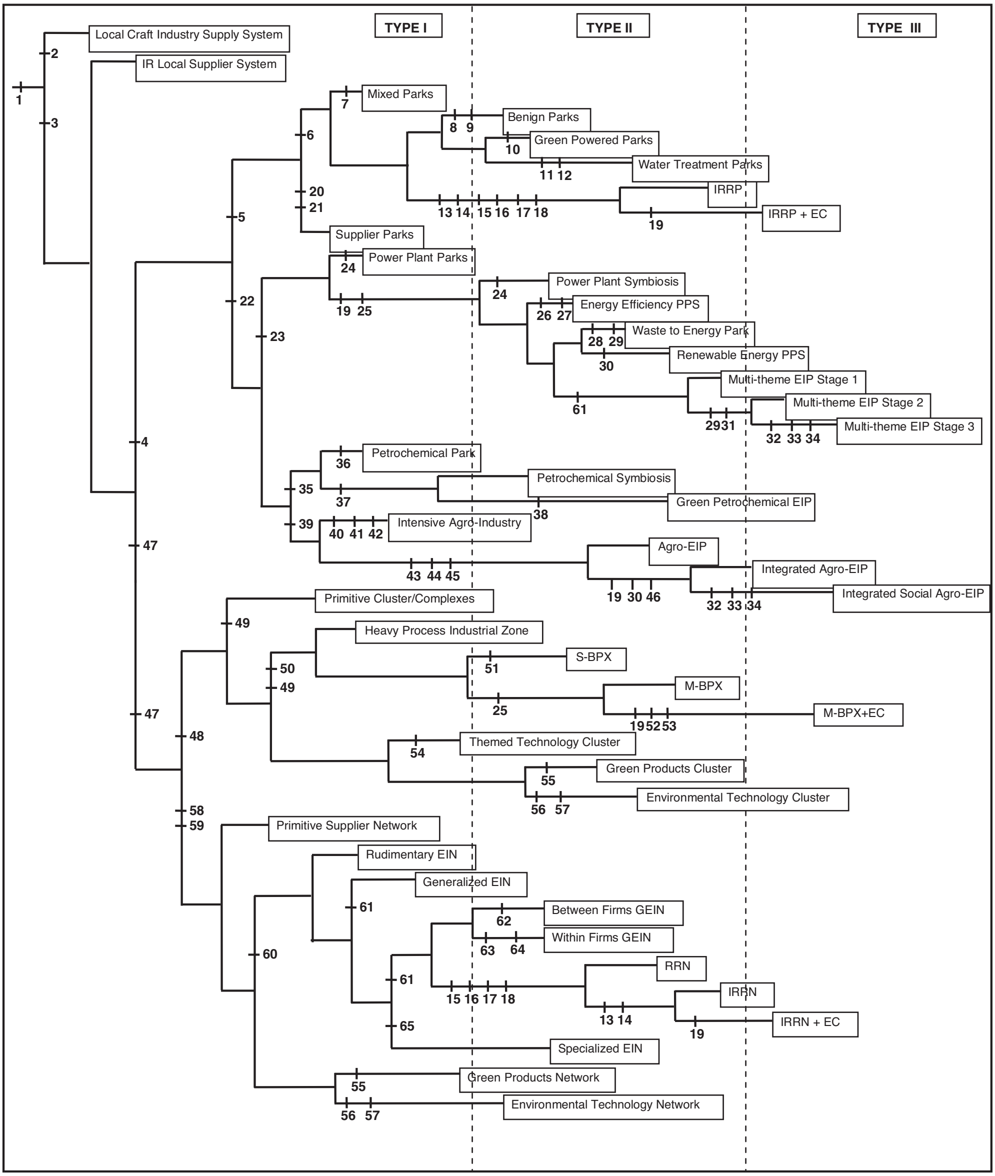

Figure 17.4 Cladogram of industrial ecosystems

are accounted for and explored through self-organizational processes, which leads to many potential future states. There are two limitations associated with these models. One relates to the generation of the diversity of interactions which is typically represented by 'noise' produced by a stochastic mechanism in the equations. The second relates to the components – although interactions are non-average, the system components are assumed to be all of an average type.

To better mimic true evolutionary processes, this assumption has to be removed so that the components are also treated as non-average. The introduction of this internal or micro-diversity takes the modelling from just blind adaptation to co-evolution; from random interactions to experiential learning, which is a more accurate representation of real evolutionary change. The 'means' and the 'end' are transitory and in continual paradoxical dialogue through feedback (Allen et al., 2007). Control is devolved from the global to local situation – a manifestation of how all the diverse behaviours perform relative to one another. Evolution involves both chance and determinism impacting the transfer of information which is imperfect and inevitably involves a degree of 'error-making' (Allen and McGlade, 1986).

This is a necessary requirement, however, and creates the forum for learning through the continual exploration of behaviour space. In summary then, assumptions are made of average interactions and components that increasingly reduce complex reality to simplicity. By removing these assumptions the potential of the model changes from being (misleadingly) predictive to explorative – the more evolution is accurately modelled the less the model is capable of predicting with a single, simple trajectory. However, the underlying, evolutionary processes give modellers a deeper insight into the system under study. Instead of prediction, different possible future states may be explored which provide modellers with the ability to reduce uncertainty and risk and to glimpse possible future system states. In reality we have one 'run', with computer simulations evolutionary runs are limitless. What may not have evolved this time for one reason (possibly chance) or another (e.g. decisions), may evolve next time.

In terms of its application to industrial ecosystems, the opinions of industrial ecologists of how the technologies, practices and policies identified in the manufacturing cladistics approach, used to define industrial ecosystem structure, interacted with one another. When the interactions between 'characteristics' or 'character-states' are collected, through, for example, questionnaires and interviews with experts, then limitless evolutionary 'runs' of industrial ecosystem evolution may be simulated. The characteristics would represent those listed in Table 17.2 (above) and include, for example, 'energy cascades', 'renewable energy', 'green chemistry', etc. The potential advantages of this approach are several. For example, a highly unique industrial ecosystem contemplating a major configurational transformation would be able to conduct a thorough exploration of the pros and cons of crucial, and perhaps not-so-crucial, decisions. Decisions may be explored time and again in, for example, different contexts or with the presence or absence of other important variables. Another advantage would be if a particular park developed a new characteristic of its own, e.g. a new system of material exchange, but were unsure of the consequences of adopting it, then the model could be applied to explore many possible outcomes of the adoption and in turn reduce uncertainty and to some extent the risk associated with change. For instance, problem practices/technologies/systems could be identified and investigated or different scenarios could be run. Furthermore, potential barriers to introducing new technologies, policies and practices could be identified beforehand and discussed and planned for in more detail.

Complexity and organizational evolution

In some recent work the idea of cladistics was used to understand and reflect on the evolution of manufacturing organizations. This used an evolutionary classification scheme pioneered by McCarthy et al. (1997), McCarthy and Ridgway (2000) and McCarthy (2005). There are now several good working examples including a cladistic classification of the automotive industry (McCarthy et al., 1997) in which the following sixteen organizational forms or species were identified: Ancient Craft System; Standardised Craft System; Modern Craft System; Neocraft System; Skilled, Large-Scale Producers; Large Scale Producers; Mass Producers (Fordism); Modern Mass Producers; Pseudo-Lean Producers; European Mass Producers; Intensive Mass Producers; Just-in-Time

Systems; Flexible Manufacturing Systems; Toyota Production System; Lean Producers; and Agile Producers.

Cladistic theory calculates backwards the most probable evolutionary sequence of events. This can be seen as being the result of micro-explorations, and then a differential amplification of systems with emergent capabilities. The evolution of the automobile production industry was studied by conducting a survey of manufacturers, and obtaining their estimates of the pair-wise interactions between each pair of practices identified by McCarthy et al (1997) and listed in Table 17.3. In this approach, the microscopic explorations consist in the attempts to connect in new practices to an existing system, with the object of improving performance and creating positive emergent capabilities.

An evolutionary simulation model was then developed in which a manufacturing firm attempts to incorporate successive new practices at some characteristic rate. The 'receptivity' of the existing complex determines which new practice will in fact be amplified or suppressed if it tries to 'invade'. In this way new ideas and practices are 'launched' at random moments in the simulation and only those that 'fit' the existing bundle of practices actually take-off. In this way the structure and identity and functioning of the organization is developed demonstrating the way that complexity, classification and evolution are all inextricably connected.

Figure 17.5 shows us one possible history of a firm over the entire period of the development of automobile production. The particular choices of practices introduced and their timing allows us to assess how their performance evolved over time, and also assess whether they would have been eliminated by other firms. As a result of the different firms experimenting over time, there is an incredible range of possible structures that can emerge, depending simply on the order in which practices are tried. But, each time a new practice is

Table 17.3 Fifty-three characteristics of automotive assembly plants.

1. Standardization of parts
2. Assembly time standards
3. Assembly line layout
4. Reduction of craft skills
5. Automation (machine paced shop)
6. Pull production system
7. Reduction of lot size
8. Pull procurement
9. Operator based machine maintenance
10. Quality circles
11. Employee innovation prizes
12. Job rotation
13. Large volume production
14. Suppliers selected primarily on price
15. Exchange of workers with suppliers
16. Socialization training (master/apprentice learning)
17. Proactive training programmes
18. Product range reduction
19. Autonomation
20. Multiple sub-contracting
21. Quality systems (tools, procedures, ISO9000)
22. Quality philosophy (TQM, way of working, culture)
23. Open book policy with suppliers; sharing of cost
24. Flexible multi-functional workforce
25. Set-up time reduction
26. Kaizen change management
27. TQM sourcing; suppliers selected on basis of quality
28. 100% inspection/ sampling
29. U-shape layout
30. Preventive maintenance
31. Individual error correction; products are not re-routed to a special fixing station
32. Sequential dependency of workers
33. Line balancing
34. Team policy (motivation, pay and autonomy for team)
35. Toyota verification of assembly line (TVAL)
36. Groups *vs* teams
37. Job enrichment
38. Manufacturing cells
39. Concurrent engineering
40. ABC costing
41. Excess capacity
42. Flexible automation for product versions
43. Agile automation for different products
44. Insourcing
45. Immigrant workforce
46. Dedicated automation
47. Division of labour
48. Employees are system tools and simply operate machines
49. Employees are system developers; if motivated and managed they can solve problems and create value
50. Product focus
51. Parallel processing
52. Dependence on written rules; unwillingness to challenge rules as the economic order quantity
53. Further intensification of labour; employees are considered part of the machine and will be replaced by a machine if possible

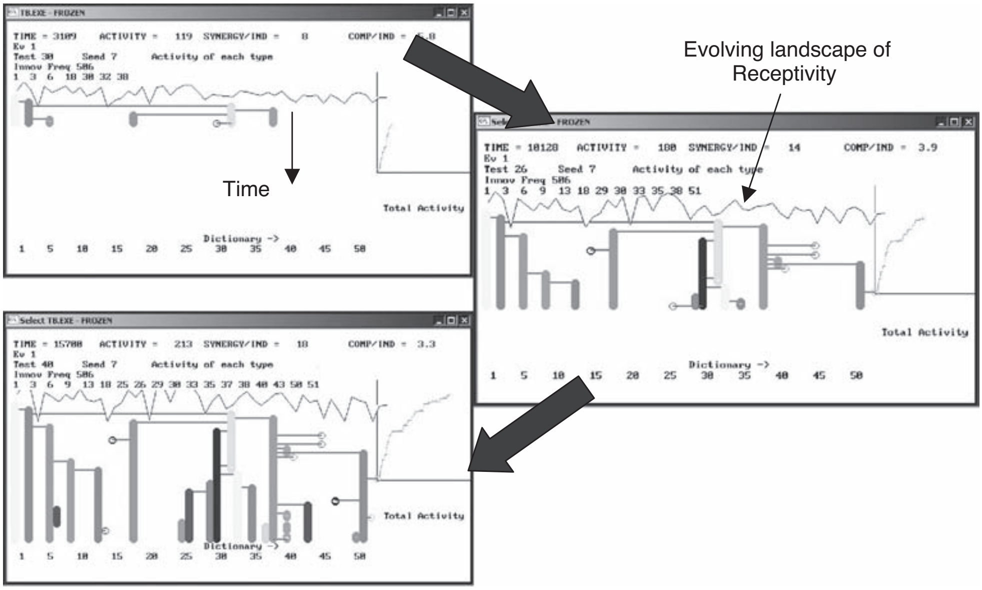

Figure 17.5 Successive moments (t = 3,000, 10,000 and 15,000) in the evolution of a particular firm. The evolutionary tree of the organization emerges over time

adopted within an organization it changes the 'invadability' or 'receptivity' of the organization for any new innovations in the future. This illustrates the 'path dependent evolution' that characterizes organizational change, already visible in the luck-dependent strategies of the preceding market strategy simulations. Here successful evolution is about the 'discovery' or 'creation' of highly synergetic structures of interacting practices and their subtle organizational requirements mean that their emergence is highly sensitive to early events in their development.

The model starts off from a craft structure. New practices are launched with an 'experimental' value of 5. Sometimes the behaviour declines and disappears, and sometimes it grows and becomes part of the 'formal' structure that then changes which innovative behaviour can invade next. The model shows how the 16 different organizational forms have increasingly high synergy as they change in the direction of lean and agile Japanese practices. Overall performance is a function of the synergy of the practices that are tried successfully. The particular emergent attributes and capabilities of the organization are a function of the particular combination of practices that constitute it. Different simulations lead to different structures, and there are a very large number of possible 'histories'. This demonstrates a key idea in complex systems thinking. The explorations/innovations that are tried out at a given time cannot be logically or rationally deduced because their overall effects cannot be known ahead of time. Therefore, the impossibility of prediction gives the system 'choice'.

The competition between different firms' exploratory pathways through time means that those who for one reason or another fail to find synergetic combinations of practice, will be eliminated. This highlights the principle of Evolutionary Drive (Allen et al., 2006b), where the micro-explorations involving the testing of new practices leads to microscopic diversity among firms, and in turn these are either amplified or suppressed by the economic competition.

In further work, these ideas have been extended to deal with the evolution of supply chains in the aerospace sector. Complex systems models have been developed demonstrating the evolution and development of supply structures that form a kind of ecology – linked to the production of a complex product such as an aeroplane (Rose-Anderssen et al., 2009a, b).

CLOSING REMARKS

In summary, instead of simply assuming that evolution must necessarily lead to waste reduction and increasing efficiency of industrial ecosystems, in reality what happens will depend on the decisions made by the agents involved within it. A systemic view provides information on the overall performance of the industrial ecosystem and can guide agents and policy makers towards decisions that can improve its overall economic and environmental performance. Evolutionary models can be used to explore the probable structural evolutionary paths of an industrial ecosystem and suggest ways in which individual agents can make successful decisions and in addition overall performance can be improved. But in considering industrial ecosystems in relation to complexity and management there is no simple proof that the disconnected evolution of individual agents will automatically lead to overall systemic optimization. In addition it is also true that individual agents within an industrial ecology usually will not be able to learn how their own decisions affect overall performance of the system. A systems representation used as a means of communication between interacting agents would allow synergetic behaviour to be identified and chosen, and evolutionary modelling could explore not only the direct consequences of an innovation or change, but also the possible succession of responses and adaptations that may follow. In this way a much broader and deeper exploration of the possible overall improvements of an industrial ecology can be made of linked firms and agents and a shared interpretive framework and eventually an emergent collective governance developed. Only then would the industrial ecosystem be able to evolve towards successful and sustainable performance.

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18

Complexity and the Dynamics of Organizational Change

Glenda H. Eoyang

INTRODUCTION

Dramatic changes in organizational environments at the end of the twentieth century and continuing into the twenty-first have driven the need for new theories and tools to cope with organizational change. At the same time, developments in understanding of nonlinear dynamics, particularly from complexity science, provide an array of new ways to conceptualize and influence change in organizations. These new approaches have introduced descriptive and explanatory metaphors to inform practice and, as a result, some long-standing dichotomies that shaped understanding of and actions toward organizational change have been transformed into 'generative paradoxes'. In the next stages of research and practice related to organization change, what is required is the development of theories and tools that can influence options for action through prospective application, translate into practice with both ease and insight, and consistently capture both the stability and disruption that are central to the complex dynamics associated with organizational change. This chapter reviews complexity-inspired perspectives on organizational change; and proposes a practical approach for moving forward that bridges between control-oriented and emergence-oriented approaches to organizational dynamics.

APPROACH

This overview of the literature seeks to present a picture that is both wide and coherent, but undertaking it presented a variety of challenges and, inevitably, trade-offs. So it is important to be clear about the approach taken.

First, this chapter focuses primarily on research published in English that explicitly applies theories and language from complexity science. But it must be acknowledged that there are practitioners implementing complexity-inspired innovations and insights who have chosen not to publish about them; there are scholars doing excellent work in languages other than English; and both researchers and practitioners often allude to patterns of complex adaptive organizational change dynamics without using complexity language explicitly (March, 1981; Morgan, 1986; Larsen, 2002). Identity and its transformation

(Bouchikhi and Kimberly, 2003), large scale change events (Eggers et al., 2002; Bunker and Alban, 2006), portfolio theory (Donaldson, 2000), and turbulent environments (Head, 2005) are examples of ways in which 'common' language of change is used to describe unpredictable and complex phenomena without explicitly drawing from the concepts and principles of complex adaptive systems. In fact, for decades, scholars and practitioners have described what is now recognized as nonlinear dynamics of organizational change. 'Given the pace of events and the turbulent environment, organizations confront tremendous problems' and '[e]ssentially, this means that organizational systems must renew themselves continuously if they are to survive in this society' (Bennis, 1969: 7). Similarly, Weick (1979) described a massively entangled and dynamic world in which individual agents engaged to change each other and to form emergent systemic patterns over time. Certainly, reconciling studies in which a complexity perspective is implicit with those that explicitly draw on concepts from studies of complex systems represents an important research frontier but is, however, beyond the scope of this chapter.

Second, both the fields of complexity science and organizational change research are quite diverse, so a single, coherent view of either – to say nothing of both considered together – presents a daunting challenge. This chapter does not presume to create order out of what might be termed the chaos of the literatures – and the sheer variety of phenomena, methods, models, and tools in both literatures suggests that convergence will not come soon, if at all – but, rather, begins to articulate some of the patterns that are forming across the two fields.

Third, the literature is deeply, though not always explicitly, divided on the question of whether 'complexity' is an ontological or epistemological reality. Because excluding either of these perspectives constrains the usefulness of theory and tools for organizational change, this chapter adopts an approach that is based on the work of Habermas (as discussed in Knorr-Cetina and Cicourel, 1981) in which intersubjective truth can emerge from truth claims that rest on objective (external evidence), subjective (personal perspective), and/or normative (group agreements) arguments and evidence. Essentially this is a pragmatic, practitioners' stance, based on the assumption that the purpose of work on organizational change is to facilitate change in organizations. Such a stance requires doses of both ontological and epistemological reality. The organization, as an object of action, must be assumed to exist, as it responds in demonstrable and unpredictable ways to action of individuals and groups. On the other hand, the organization's relevant characteristics at a particular point are determined by the perspectives, experiences, and world views of the engaged actors. This chapter explores this dichotomy and its relevance to complex organizational change, but an acknowledgement of the pragmatic stance helps to establish the assumptions on which this chapter is based.

Fourth, the nature of complex adaptive systems sometimes precludes traditional research approaches to theory building and testing where rigor of research is judged according to its validity and reliability, so these criteria have not been applied to filter articles presented. Organizations as complex adaptive systems are assumed and observed to be sensitive to initial conditions, path dependent on their histories, (frequently) high dimension, and (usually) open to external influences. As a result, it is unreasonable to expect any two situations to be similar enough to support validity or to be predictable enough over time to allow for reliability. New definitions of rigor and new methods of both positivistic and interpretive research are emerging to support innovative ways of seeing and documenting phenomena that are either local and particular or global and generalized (Vesterby, 2008). For this reason, no claims are made as to the boundaries of generalizability of the findings from the studies cited in this chapter, and the power of many of the findings will remain an empirical question.

Fifth and finally, the substance of nonlinear dynamics as applied to human activity can be understood and incorporated in four different ways: *practice*, *descriptive metaphors, explanatory metaphors*, and *mathematics* (Eoyang, 2004). Practice executes change in organizations; descriptive metaphors inform shared narratives and suggest reasonable options for action; explanatory metaphors invite qualitative analysis and support interpretive theory building, testing, and adaptive action; while mathematics provides a level of 'objective' rigor. This chapter includes examples of all of these approaches but does not presume to judge that any is superior or inferior to the others. All approaches to applications of complexity science bring certain benefits and risks in understanding and influencing organizational change. Responsible research and practice require that both purveyors and users of research are aware of where they stand on the continuum between superficial description and deep, causal understanding (Palmer and Dunford, 1996).

Because approaches emphasizing practice and mathematics are well handled in other chapters in this Handbook, this chapter focuses more on descriptive and explanatory metaphors. Descriptive use of complexity metaphors consists primarily of retrospective analysis of organizational change using visual metaphors from complexity science (Wheatley, 1992; Hock, 2005). Used to describe either the preconditions or the outcomes of change processes, descriptive metaphors label and categorize patterns, rather than describing how or why change happens. These organizational applications of the metaphors may be more or less sensitive to the nuances of the physical phenomena from which the metaphors were derived. Various critiques have been made of loose applications of complexity metaphors to organizational change (Fuller and Moran, 2000; Stacey et al., 2000; Smith, 2005; Paley, 2007), but some argue that rigid application of the language is not necessary for support of organizational theory and practice (Van Uden, 2005).

Explanatory metaphors, on the other hand, seek to articulate how the mechanisms of organizational change mimic the mechanisms of nonlinear change in physical or biological systems (Guastello, 1995; Lissack, 1999; Poole et al., 2000; Eoyang, 2001; Alaa, 2009). Explanations provide the ground for analysis and intentional action to influence change in complex adaptive systems. The mechanisms for complex change in biophysical systems involve subtle relationships and difficult mathematical concepts, so applications of explanatory metaphors to organizational change require a higher level of rigor and more profound disciplinary background than merely descriptive metaphors.

Adopting this approach, this chapter surveys the academic and practice literatures that explore and characterize ways in which organizational change theory and practice are being altered as a result of developments in complexity science.

FROM NEWTONIAN TO COMPLEXITY PERSPECTIVES

What has come to be called the traditional Newtonian view of change was grounded in features of the physical world. Time, mass, and distance were the fundamental units in which change of any kind could be described or explained. This worldview generated particular ways to characterize organizational change, built on particular understandings of key concepts. *Inertia* implied that the organization would not change unless acted upon by an outside force. *Resistance* implied that individuals and organizations would push back against efforts toward change. *Progress* implied that there was some pre-determined end toward which an organization could and should move. *Momentum* implied smooth and predictable paths of change. *Power* implied the ability to move an organization forward as if it were a passive object. *Alignment* implied a clear need for homogeneous commitment to a single goal. All of these and many other physically grounded expectations were sufficient to describe and influence organizational change when organizations could be conceived as working in Newtonian contexts – relatively closed boundaries, small and consistent numbers of relevant factors, and linear causality. Various approaches and descriptions of organizational change reflect and/or critique these fundamental assumptions (Kelly and Amburgey, 1991; Tulloch, 1993; Tetenbaum, 1998; Knowles, 2001; Mason, 2004; Van Tonder, 2004).

Over the history of organization development and organization change practice and theory, various attempts have been made to explain the dynamic nature of change. Action research explored an understanding of how consultants, change agents, and organizational patterns interacted over time in complex ways. Organizational change was characterized as a process of unfreezing, moving, and refreezing. Various scholars and practitioners examined multiple phases of planned change. Processes were defined for client engagement over time. Others reframed the client engagement sequence to make it more dynamic and adaptive. Contingency theory strove to capture the cause and effect relationship between an organization's external environment and its internal structures and processes. In each of these developments, scholars used biological and physical metaphors from their contemporary science to describe the phenomena they observed in the course of organizational change.

At the end of the twentieth century, authors from around the world and across the economic and political spectra extolled the changing nature of change in human systems (Cleveland, 2000; Dawson et al., 2000; O'Hara-Devereaux, 2004; Friedman, 2007, 2008). Globalization opened traditional system boundaries. Emergent and unpredictable processes influenced many aspects of personal and organizational experience. Political unrest, religious fundamentalism, and antibiotic-resistant bacteria spread like wildfire. Technology increased the speed and reliability of communication. Economic and political conditions encouraged mobility and resulted in massive increases in ethnic and cultural diversity. Product development and obsolescence cycles accelerated. Social networking and other Internet 2.0 tools emerged. Information was ubiquitous. Economic and lifestyle disparities expanded. The work force aged. Customers became more discerning and demanding. Everything that supported stability and continuity of organizations was compromised. Uncertainty increased. Organizational change became so unpredictable and uncontrollable that even the appearance of control became unsustainable. These conditions of radically open system boundaries, high dimension interaction, and nonlinear causality made the old metaphors of physical change insufficient to help people understand or influence change in this new organizational environment (Chaharbaghi and Nugent, 1994; Hodge and Coronado, 2007). Individuals and organizations needed new ways to think about, talk about, and interact to encourage organizational change.

The emerging nonlinear sciences of chaos and complexity have begun to provide these, offering new options for thinking and action toward organizational change (Lindberg et al., 1998; Michaels, 2001). Nonlinear dynamics focuses on change that may or may not involve Newtonian assumptions of absolute time, scale-dependent space, or physical mass. Prigogine and Stengers (1988) describe the role of irreversible time. Bak (1996) and others focus on scale-free phenomena in which physical size and its suggestion of space are completely relative. Organizational change deals with conceptual, relational, and cultural entities whose 'weight' cannot be measured with scales. Concepts and tools drawn from chaos theory, complexity science, and complex adaptive systems and other closely related branches of nonlinear dynamics have been used to describe organizational dynamics. As a result, traditional descriptors of organizational change are replaced with ones that better match the real-world phenomena of change in post-Newtonian organizations – butterfly effects, fractals, self-organized criticality, emergent networks, attractor regimes, and so on (Eoyang, 1997). On the other hand, some applications of nonlinear dynamics to describe change in human systems have been critiqued as insufficient to explore the multi-faceted dynamics of organizational change (Dooley and Van de Ven, 1999).

In spite of concerns about the possible misapplication of metaphors from complexity science, the language has proven useful to respond to a variety of concerns. The necessity for a new organizational change paradigm (Falconer, 2002) has been met with responses that explicitly adopt a complexity perspective. Case studies have illustrated many of the dynamics of complexity in organizational change as well as some practical applications of complexity science metaphors and tools for understanding and influencing individual, procedural, and organizational change (Rowe and Hogarth, 2005) as well as the emergence of new organizational communities (Chiles, et al., 2004). New books that apply concepts and tools from complexity to various aspects of human systems continue to enter the market (Hudson, 2010).

This chapter explores three facets of this transformation of thinking and action for systems change. First, the most common complexity concepts are examined, as well as the ways in which those concepts have been used to explore, explain, and encourage organizational change through both practitioner and academic literature. Second, the changing worldview is examined by exploring how dichotomies of Newtonian change are converted into generative paradoxes in the world of complex, nonlinear change. Finally, possibilities for future exploration are suggested.

DESCRIPTIVE AND EXPLANATORY METAPHORS

Managing successful change requires an understanding of the current environment as well as a portfolio of descriptive and explanatory models to inform action. The sheer diversity and contextual sensitivity of complex organizational systems requires that the practitioners have access to a wide range of theories and tools that might be applicable. Some research has compared and contrasted multiple organizational change models (Kilduff and Dougherty, 2000; Fernandez and Rainey, 2006). Others look broadly at applications of nonlinear dynamics to organizational change (Kiel, 1989; Goldstein, 1994; Dooley and Van de Ven, 1999; Zimmerman, 1999).

This section considers some of the most common metaphors inspired by complexity science and where and how they have been used in research and practice. As alluded to above, descriptive and explanatory metaphors draw language and models from complex adaptive systems and apply them to patterns in organizational change that seem to be similar in cause, outcome, or process. Some features of nonlinear dynamical systems (such as strange attractors) are more difficult than others (such as butterfly effects) to recognize, describe, and document through analogy or isomorphism to organizational change phenomena. This is because the phenomenon in the natural world is more complicated and subtle than implied in the metaphorical description. When the complexity descriptor is incorrectly or incompletely understood, then the metaphorical application to the organizational context will be flawed. Opinions differ widely on the appropriate use of even the most well reasoned complexity metaphors in describing organization change, still the metaphors continue to appear in both research and practitioner journals. Five explanatory and descriptive metaphors from complexity science have most often been alluded to in organizational change literature: fractals, simple rules, self-organized criticality, emergence, and adaptation.

Fractals

A fractal is a geometrical object that is generated by iteratively solving a nonlinear equation and plotting the stability of the solution set for separate, individual initial starting points (Briggs and Peat, 1989). The resulting pattern is complex, coherent, and scale-free, which is to say that similar shapes appear regardless of how much the image is magnified. Fractals are used metaphorically in two ways when applied to organizational change.

First, the idea of the fractal has been used to represent a constant principle, rule, or idea that supports iterative applications and generates a complex but coherent system-wide image over time (Zimmerman and Hurst, 1993). For example, the concept of *identity* can be considered to be a 'seed' around which fractal patterns form (Bouchikhi and Kimberly, 2003). If all members of the group carry the same understanding of their own identity, then as they interact over time (internally and externally to the group), shared and coherent cultural and social patterns emerge. Spiritual traditions may function in a similar way, as they support complex interdependencies and influence system-wide coherent organizational change in complex systems. Examples of the fractal dynamics of spiritual traditions have included Confucianism (Tuan and Ryan, 2000) and mindfulness practice (Langer and Moldoveanu, 2000). In these situations, core principles are held by all practitioners and systemic patterns emerge at levels of family, group, institution, and community.

The other way that fractals are used metaphorically is to focus on the scale-free nature of the fractal pattern. This explicit metaphor of fractals can be applied to explore relationships within and across hierarchies, as well as the influence of individuals as they engage in organization change. For example, Levick and Kuhn (2007) explore how fractal patterns influence organizational management both during times of stability and of change. The metaphor of fractal patterns can also be used to diagnose and assess readiness for change when patterns of behavior are detected in all levels and all parts of an organization. Eoyang (1997) describes an approach for using fractal images to support discussions that prepare individuals and organizations for change.

Simple rules

Simple rules, sometimes called minimum specifications, derive from applications of agent-based computer simulation models. In the computer applications, entities are programmed to respond to stimuli according to a short list of simple rules. As a result, they can self-structure into coherent, system-wide patterns (Wolfram, 2002). This metaphor has been applied to suggest ways to gain alignment during organizational change without over-constraining individual agents (Zimmerman et al., 2001; Kennedy, 2002; Eoyang, 2007). Holladay (2005) reports the use of simple rules to inform school reform, student learning, and reduced racial tensions in an urban school district. Despite these advances, it is important to note that simple rules have also been critiqued as inappropriate in describing self-organizing phenomena in human systems (Stacey, 2001; Paley, 2007; Snowden and Boone, 2007). Two arguments stand against use of simple rules in dealing with organizational change. The first involves free will: Rules do not constrain the actions of people. The second involves specificity: Rules that are general enough to apply to all are devoid of local or individual significance.

Self-organized criticality

Self-organized criticality refers to the way in which internal dynamics can result in unpredictable system-wide transformations. Bak (1996) used sand piles to simulate how accumulating tension at one level of scale can burst forth to reshape another level. The most familiar physical example is the avalanche, where the side of a mountain can appear to be stable and suddenly come crashing down. Gladwell (2002) popularized the notion as the 'tipping point', though his focus was simply on a single point of transition, as opposed to the dynamical process leading up to and following after the critical point. Power law dynamics relate to the relative sizes and frequencies of system collapses under conditions of self-organized criticality. Sometimes referred to as 'punctuated equilibrium', discontinuous change related to self-organized criticality has been studied both with computer simulation models (Gersick, 1991; Sastry, 1997) and contemporary case studies (Romanelli and Tushman, 1994; Lichtenstein, 2000; Siggelkow, 2002) to explain the tendency of a complex system to absorb information and energy over time without apparent change, then to break through into a new structure with surprising speed and clarity.

When the self-organized criticality metaphor is applied to organizational change, it is usually used to characterize the relationship between continuous and discontinuous change. The question of continuous or episodic change has been a perpetual question in organization change theory (Anonymous, 1998). Inter-level influence and interdependency are central to the change through self-organized criticality. Organizational change theorists have explored the forces and phenomena of self-organized criticality (Dansereau et al., 1999; Burns and Nielsen, 2006). They have found that both the qualitative patterns of the process of self-organized criticality and the quantitative patterns of power law dynamics are relevant to retrospectively describe unpredictable, discontinuous, and cross-scale change in organizations.

Emergence

Emergence is widely regarded as the process by which a complex combination of agents generates system-level phenomena that are qualitatively different from the sum of the system's parts. This metaphor has been used widely and in a variety of contexts. Some case study research projects indicate that organizational patterns of behavior cannot be explained from the analysis of parts. Rather, they emerge as systemic patterns from across a wide range of situations and stimuli (Bella, 1997; Hafsi, 2001). Other case studies have indicated that organizations adjust most effectively to change when situations are not over simplified and when individuals and teams are allowed to adjust to changes over time as patterns emerge and individuals and groups respond to the emergent patterns (Carroll and Hatakenaka, 2001).

Turbulent environments generate unplanned or 'emergent' behaviors, so they require more nimble, radical, fast, and disruptive responses. Often a capacity to respond to emergent events is acknowledged to support organic (rather than mechanical) and bottom-up (rather than top-down) change processes. While organic, emergent and mechanical, planned change can be contrasted, the two can also be seen as complementary. Often both are required to meet the needs of stability and innovation in situations of organizational change. A combination of both top-down (hierarchically imposed) and bottom-up (participatory) forces is most effective to leverage the power of complex organizational relationships as new patterns emerge over time (Huy and Mintzberg, 2003). Historical views of emergence in complex social structures at many levels can provide insights into the ways in which resource ownership and procurement influence emergence of organization and other social structures (Read, 2002). Emergence can also be used as a way to understand, explain, and intervene in the creative engagement associated with design processes. Standing between autonomous creativity implied by radical, *self*-organizing responses and highly constrained processes of 'designing for others', a mix of individual creativity and environmental sensitivity replaces the top-down/bottom-up challenge of design with and inside out/outside in models for organizational change (Rowland, 2004). Swarm intelligence is another emergence-inspired metaphor that is drawn from the biological world to describe self-organizing behaviors of human systems (Garnier et al., 2007).

Most applications of emergence in organizational change literature are descriptive in nature, but some have created explanatory metaphors by defining factors or conditions that influence self-organizing or emergent processes. Alaa (2009) articulated four factors that supported emergence in a software development project, including social constructions, adaptive factors, enabling infrastructure, and control factors. Eoyang (2001) describes three features that influence the speed, path, and coherence of emergent processes. Those three are related to each other in complex, nonlinear ways, and include the container, which holds the agents together; differences, which articulate the pattern and establish motivation for change; and exchanges, which support transfer of material and information among agents. Both of these explanatory models can be used retrospectively to analyze historical cases, or they can be used prospectively to inform action that encourages and influences organizational change.

Adaptation

Adaptation has arisen as one of the most frequently addressed aspects of complexity science in organizational change because it appeals to both common sense and technical understandings. Drawn from ecological and evolutionary theories of change, adaptation refers to the ways in which living organisms change their internal structures to enhance fit with the environment and improve possibilities of success. Along with its closely associated biological metaphor of evolution, adaptation is used as a way to consider many facets of organization change (Fulmer, 2000).

Evolution and evolutionary dynamics represent some of the earliest ways in which complex change in organizations was described (Hannan and Freeman, 1989; Finne, 1991; Baum and Singh, 1994; Knyazeva and Kurdyumov, 2001). Evolutionary adaptation toward fit with internal and external patterns is discussed in case studies (Siggelkow, 2002). One benefit derived from thinking about organizational change as adaptation through evolutionary emergence is that a single causal structure can be relevant across levels of change – individual, organizational, cultural, and biological levels (Commons, 2008). The pace and direction of organizational change can be seen as driven by both internal and external factors, e.g. internal relationships can generate apparent resistance at the same time that evolutionary and revolutionary external changes occur. In practice, therefore, these two domains of change are part of the same evolutionary process (Miller and Friesen, 1980).

The concept of co-evolution, in which two entities adapt to each other over time, has also been applied to look at organization change in hypercompetitive environments (Rindova and Kotha, 2001). Specifically, it has been argued that engagement between and among team members, between teams in the same organization, and active competition among firms all increase the creative capacity in product development. More generally, when agents in a complex system adjust their internal characteristics to better fit with external agents to improve survival, their change processes can be characterized as ‘co-evolution’.

Adaptation is a familiar concept for scholars of organizational change, though it is not always used with the full range of nonlinear dynamical implications. A wide range of specific tools are used to address adaptive issues in organizational change. Various technical and management strategies have emerged to articulate the ways to resolve lack of fit between the demands of the marketplace and organizational policies, procedures, processes, and practices (e.g. Donaldson, 2000). Economic analysis theories distinguish among the abilities of various organizational types to respond to levels of uncertainty (e.g. Sorgaard, 1989). Employee turnover, for example, has been explored as one mechanism that drives disruption and adaptation in organizational change (Baron et al., 2001). Each of these approaches to adaptation and organizational change unveils a different facet of the complex process of change in organizations. A qualitative concept of 'adaptation' is familiar outside of the complexity literature, but complexity science can provide a more precise definition that supports both practical application and rigorous research of this unpredictable process of organizational change.

In addition to considering the organization-wide implications of adaptation, some research has focused on how individuals adapt to influence organizational change. In these contexts, difference becomes a driving force for change. Individual and group identity and the need to adapt in order to resolve differences between the one with the other has been shown to be a critical factor in organizational change (Seo and Creed, 2002; Snowden, 2002; Kuhn and Corman, 2003; McCarthy et al., 2005; Beech et al., 2008). Dialectical engagement can be considered a mechanism by which entities resolve differences to adapt or co-evolve. Differences between self and other, individual and organization can be seen as forces that motivate and actuate organizational change (Myeong-Gu and Creed, 2002). Dissonance between context and organizational action (Greenwood and Hinings, 1996), self and other (Durand and Calori, 2006), production processes and communication structures (Sandaker, 2009), cultures in mergers (Baskin et al., 2000; Zimmerman and Dooley, 2001; Mitleton-Kelly, 2006), and logics of action (Bacharach et al., 1996) are used to explain the mechanisms and motivations for organizational change and adaptation over time. Complexity science provides metaphors and tools to explore creative tensions, high dimension differences, dynamic response to demands for fit, and multi-level relationships, so it can support a more rigorous and nuanced approach to understand difference and its impact on organizational change.

Stacey (2001) focuses on the interactions among individuals in a complex environment as the cause for radical innovation and emergent adaptation. Challenging the power of systems and systemic thinking, he posits that complex responsive processes are at the core of individual and collective action that drives organizational change.

The need to adapt in times of turbulent change is pretty obvious, but the capacity to adapt to the right things at the right speed while maintaining organizational stability is not so clear. The tension between sustaining identity and adapting to improve fit among individuals or with organizations is an issue in many cases where adaptation might be considered a winning strategy (Cilliers, 2006; Glor, 2007). This problem of competing demands for stability and change also influences approaches to innovation. As a special case of adaptation, innovation also demands continuity coupled with radical change (Hage, 1999; Jarratt, 1999; Rycroft and Kash, 1999; Suchman, 2001; Kash and Rycroft, 2003). Complexity science provides theory and tools to formalize research and practice in these situations of unpredictable and uncontrollable organizational change.

Each of these five metaphors drawn from complexity science can be evocative for persons who study or influence organizational change. However, they are defined and applied in rather idiosyncratic ways so that a coherent, broadly accepted collection of key metaphors has not yet emerged in the field. Continued conversation among scholars and practitioners will be necessary before a coherent, shared understanding of complex organizational change will emerge.

FROM DICHOTOMIES TO PARADOXES

The current literature on organizational change as complex adaptation is rich in its diversity, but limited in its coherence. One possible resolution of the current cacophony is that a single view of complexity and its meaning for organizational change could emerge as a dominant set of theories and tools. Though efficient, this outcome would limit the flexibility and applicability of these theories and tools in the world of organizational change, which is itself quite diverse. Another resolution would be to continue the anarchy of the past, while each practitioner and researcher follows an idiosyncratic argument from theory and practice of the past into theory and practice of the future. In the interest of coherence, however, a complex adaptive alternative might be considered – one in which the key dichotomies of the past are recast as establishing creative tension, to provide some level of bounded instability in which new theory and practice can continue to emerge. Eight creative tensions emerged across the articles reviewed for this chapter. With a Newtonian perspective on organizational change, these appeared as dichotomies that demanded a choice between the one and the other. From the complexity perspective introduced here, each pair can be seen as forming a generative relationship that will provide a map of the territory for complex organizational change theory and practice. Each of the complementary pairs is described below, and options for action in research and practice are suggested.

Explicit and *implicit use of complexity concepts*

One on-going question in applications of complexity to organizational change involves the language that is used to introduce the concepts and actions. As described above, the literature includes references to complex dynamics without explicitly invoking the language of complexity science. Sometimes, the concepts are made explicit intentionally (Webb et al., 2006), other times the nonlinear dynamics are not discussed at all, or they are renamed in language that is more familiar or comfortable. Implicit reference to the complex dynamics builds a bridge to traditional theory and to clients' practice worlds. Explicit complexity language provides opportunities to build and test a mature formalism of language and method. As applications of complexity to organizational change evolve, neither of these extremes will serve the field well. Rather, complexity-inspired vocabularies should be used consciously, and scholars as well as practitioners should assume a critical stance regarding the use of both qualitative and quantitative complexity metaphors.

Change and *stability*

In complex systems characterized by emergence, a tension arises between the stability necessary to sustain identity and the change required for adaptation. Cross-level relationships can be used to understand and intervene to maintain this tension in a productive balance (Leana and Barry, 2000). While Stacey (2001) explains the mechanisms of transformation strictly through complex responsive processes, fractal patterns and the structural meta-stability of self-organized criticality speak to the simultaneous need for order and emergence. Scholars, practitioners, scholar-practitioners, and practitioner-scholars need to acknowledge that sustainable organizational change requires both stability and flexibility, both continuity and disruption, both ties to the old and stretches to the new. If complexity-inspired research and practice lose either of these dynamical forces, they will risk falling into Newtonian stasis or flying off into theoretical and practical anarchy.

Positivistic and *interpretive research*

Traditionally, a researcher had to choose one or the other: (typically but not necessarily quantitative) positivism or (typically but not necessarily qualitative) interpretation. The underlying ontologies and epistemologies are sometimes so radically different that no theory or tool could embrace both. Fortunately (or unfortunately, depending on your stance), this either/or approach to research is not useful in the context of complex systems. Depending on the circumstances, some facets of a situation can and should be bounded and measured while other facets will enfold such high dimension, unique, and unpredictable phenomena that measurable indicators are meaningless. Neither approach is better or worse in any absolute way, but both can be badly abused if they are not fit to the environment and the research questions to be explored. The use of mixed methods and the choice to stay in generative engagement with diverse colleagues will allow the field to transcend this dichotomy.

Individual and *organizational change*

Traditional theories of change often forced change agents and researchers to focus on only one level of the change process: individual or organization. Complexity science opens a new path in which system-wide patterns of the whole emerge from semi-autonomous activities of the parts at all levels. Many outstanding questions remain about this connection between individual and collective change, but the metaphors and tools of complexity provide opportunities to articulate and address those questions in ways that were not possible before. This distinction is particularly clear in explorations of adaptation, where individual learning and change inform and are informed by evolution of organizational policy, procedures, practice, and identity.

Episodic and *continuous change*

Many researchers and practitioners used to ask whether organizational change was episodic or continuous. From a Newtonian point of view, this is a critical question, but from a complexity point of view it is not. Given the dynamics of scale-free patterns and self-organized criticality, it becomes obvious that organizational change is both. Continuous, incremental change can persist in some parts or at some organizational levels while episodic, catastrophic change occurs in others. Our theories and practices for organizational change must account for both to happen simultaneously. Even more, they must account for the interdependencies between the two.

Retrospective and *prospective analyses of change*

For many years, complexity scholars were focused on retrospective analysis. Nonlinear dynamics were only observed in the rear view mirror, so research focused on case studies and deconstructing previous theory and practice. As a developmental stage, that was not a bad thing, but if complexity approaches are to be more than interesting fads, they must add value to decision making and action through prospective analysis as well. Research and practice should innovate and test methods for understanding and influencing current complex patterns to generate patterns of the future. This approach will involve explicit testing of theories that are used to anticipate outcomes and evaluate performance against them over time. Otherwise, applications of complexity science to organizational change will become merely historical reflections of nonlinear dynamics in human systems, not contributions to adaptive capacity for individuals and organizations.

Complexity as an epistemological and *ontological phenomenon*

Philosophers and physical and social scientists have been preoccupied with this dichotomy for decades if not centuries. Two factors entice us to move beyond this distinction and into a new way of thinking of ourselves as investigators in the world. First, complex adaptive systems worldview assumes a backdrop of reality that can be continually transforming. The pace and complexity of the ever-changing context precludes the opportunity to separate what is happening from my ability to know what is happening. According to some threads of quantum physics, humans may even create physical reality with our thinking. Second, neither scholars nor practitioners have time to divorce themselves from innovative and meaningful action. At the point of action and receiving feedback to our action, the boundary between ontology and epistemology becomes a thin veil. When practitioners (or their clients) are in adaptive engagement with a complex environment, thinking and real-world causality merge. Certainly, one lesson that has been learned by viewing organizations as complex adaptive systems is that active engagement in the moment is the means to emergence and adaptation for survival.

Knowledge for theory and *for practice*

The journal *Emergence: Complexity and Organization* has wisely brought together scholars and practitioners to share their findings about complexity and human systems. As a result every reader is invited into a world of praxis, where theory is practice-informed and practice is theory-informed. The radical uncertainty, contextuality, and immaturity of this work mean that neither practice nor theory can stand alone in any coherent or meaningful way. As inquirers in this field, each of us must concern ourselves with both sides of this traditional dichotomy.

LOOKING FORWARD

As students of complex change work within the creative tensions of these traditional dichotomies, they will continue to frame and pursue questions about the dynamics of organizational change. Sometimes those questions will emerge in the midst of action for leaders or consultants, and sometimes those questions will emerge in the midst of theory building or testing. As the field moves forward to establish a stronger foundation of theory and practice, scholars will address a variety of questions, including the following.

What practical theories and tools can help individuals and organizations to be most productive in times of rapid change in complex environments? Complex change will require a different kind of change-supporting tool than simple, linear change. A single developmental cycle, a list of goals, a set of best practices will have limited usefulness because of the complex diversity of nonlinear change. On the other hand, the possibility lies open for tools that assess current patterns and look toward future possibilities, that encourage reflective praxis, and that embed well-grounded complexity science metaphors in productive action.

Some of the field's more practical researchers are engineering new tools and methods and making them available (Olson and Eoyang, 2001; Zimmerman et al., 2001), but the cycle time for development and dissemination is long. More people in more places need to be sharing their innovative products with others through peer reviewed journals, conferences, and web communications.

What vocabulary is appropriate for scholars and practitioners to see, describe, and influence the dynamics of organizational change, and how can it be developed? Such a common language will support both theory and practice as researchers, practitioners, and consumers share their perspectives, discoveries, and frustrations. It will help individuals and groups to be conscious when choosing implicit or explicit references to complex change. Falconer (2002) begins that process by encouraging a systemic view of complex adaptive change. Eoyang's (2001) Container, Difference, Exchange (CDE) Model and Ng's (2003) Strength-Power-Diversity (S-P-D) Model provide options that enfold the multiple dimensions of complex dynamics into simple, elegant, actionable, explanatory metaphors.

CONCLUSION

This chapter explored applications of complexity science to organizational change.

There was a time not too many years ago when chaos, complexity, and complex adaptive systems were foreign to both researchers and practitioners. Today, not only are these terms getting wide-spread acceptance, but the dynamical nature of organizational change is widely acknowledged. The challenge now is to use emerging insights about complexity science to accelerate theory development and to inspire practical innovation.

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19

Complex Thought, Simple Talk: An Ecological Approach to Language-Based Change in Organizations[1]

John Shotter and Haridimos Tsoukas

INTRODUCTION: THE NEED FOR AN ECOLOGICAL APPROACH TO LANGUAGE-BASED CHANGE

Modern science developed by privileging the general and the abstract over the particular and the concrete (Toulmin, 1990; Tsoukas, 2009a). It has taken its objects of study to be composed of discrete things rather than evolving, situated relationships. The singular and the particular have turned out to be too intractable for traditional scientific thinking and needed to be either avoided or subsumed under generic categories (Tsoukas, 2005a: 213–215). Scientific triumphalism in conquering the singular was expressed by Medawar (cited in Feyerabend, 1987: 122) as follows: 'In all sciences we are progressively relieved of the burden of singular instances, the tyranny of the particular'. In organization science, Thompson (1956: 103) expressed best the scientific embarrassment before singularities: 'If every administrative action, and every outcome of such action, is entirely unique, then there can be no transferable knowledge or understanding of administration.'

However, such an epistemological orientation contradicts common experience; situational novelty is what practitioners face all the time (Vickers, 1983; Buchanan, 1999). Follett (1924), a perceptive student and keen practitioner of management, captured, a long time ago, the relational world, a world of singularities, practitioners live in:

> As we perform a certain action our thought towards it changes and that changes our activity. […] You say, 'When I talk with Mr. X he always stimulates me'. Now it may not be true that Mr. X stimulates everyone; it may be that something in you has called forth something in him. […] I never react to you but to you-plus-me; or to be more accurate, it is I-plus-you reacting to you-plus-me. (Follett, cited in Weick, 1995: 339).

Relationality, and the emergent uniqueness it brings about, has traditionally been too difficult a concept to work with in mainstream organization studies. Even when it has been considered, the prevailing imagery has been that of discrete entities, externally – causally, mechanically – related. Change in a system is, thus, thought to be brought about by one entity impacting on another (cf. Weick and Quinn, 1999; Tsoukas and Chia, 2002).

In this chapter, we will argue that an alternative – ecological – imagery, inspired by complexity science (Tsoukas, 2005a: Chs. 9–12), which is attentive to relationships and the emergent behaviors they lead to, does more justice to common experience of change in organizations than mainstream perspectives do, especially if it takes language seriously. When I-plus-you and you-plus-me engage in conversational interaction, something unique may potentially happen, which is unlikely to be captured by mechanistic forms of inquiry. By contrast, the relational imagery complexity science brings forward enables us to better understand and work with relational uniqueness and emergent change.

A look at the relevant management literature shows that while behavioral and cognitive change have received a great deal of attention in the past, focusing on the role of language in bringing about change in organizations has not earned wider recognition until relatively recently (Tsoukas, 2005b). Yet, for practitioners, the role of language can hardly be overestimated: after all, rational authority is primarily exercised through the word (Watson, 1994; Hirschhorn, 1997). For organization theorists at large, exploring how language is used in organizational contexts and how language-in-use is inherently organizing, are increasingly becoming important foci of research (Cooren, 2001; Westwood and Linstead, 2001; Holman and Thorpe, 2003; Grant et al., 2004; Fairhurst, 2007). A useful way to understand research on language-based change in organizations is to see it as falling along a continuum, depending on how language is viewed: at the one end language is seen as a medium through which cognitive change is effected, while at the other end language is variously seen as constitutive of change.

Argyris was one of the first researchers to recognize that what people in organizations think, is related to what they think *with* – the reasoning they employ. For him change in organizations is a primarily cognitive task: effective learning (hence, change) 'is a reflection of how [organizational members] think – that is, the cognitive rules or reasoning they use to design and implement their actions' (Argyris, 1991: 100). These rules are a 'kind of "master program" stored in the brain, governing all behavior' (*op. cit.*). Pushing the cognitive perspective to its limits, Argyris draws the analogy between defensive reasoning blocking learning to a hidden bug blocking the execution of a computer program. The key, for him, is for managers and employees alike to learn to *reason productively* – only then deep learning is unblocked and effective change is brought about. Language features in Argyris' account insofar as it is the mere *medium* through which deep-seated cognitive rules of reasoning, grounded in basic governing values, are instantiated (Argyris, 1990, 2000).

For other researchers, influenced mainly by discursive psychology, discourse analysis and communication theory, language is of primary importance in bringing about change in organizations, since the latter are seen as networks of conversations (Taylor and Every, 2000). If individuals start talking differently about the world they experience, they will make a difference – they will produce change. Change in language amounts to change in how problems are viewed, experienced and managed. Notice, however, that for this perspective, there is no such a thing as *the* change – rather there are thematic narratives of change in which first-order realities (events, facts) and second-order realities (interpretations) are collapsed. Generating and managing change is a matter of shifting conversations, since when this happens, people shift to what they talk about and pay attention to. Here are a few indicative examples of this type of research.

Ford and Ford (1995) have argued that change is constituted by different types of conversation (i.e. initiative, understanding, performance and closure conversations), each of which draws on particular speech acts. Language now is not viewed as a mere medium but as co-extensive with change: change is change *in* language, rather than change through language. In a similar vein, other researchers have drawn on narrative therapy to point to the importance of story-telling (Barry, 1997; see also Gabriel, 2004). In so far as people in organizations tell stories about themselves, change comes about by telling *different* stories, while the work of the change agent is to facilitate the process of story re-telling. Drawing on Bakhtin, Anderson (2005) has skillfully shown how the discursive practice of represented voice allows organizational members to both stabilize the organization through treating organizational routines as genres of speech ('what usually happens' via 'what is usually said') *and* change those routines by considering how new practices might sound in the future by articulating the proposed change in the voice of an organizational member (particular individual or category member). By envisaging and enacting likely conversations in the future, the merits of proposed changes are judged from multiple perspectives. By viewing routines as genres of speech, organizational members are able to envisage different kinds of future conversations, thus generating different kinds of change.

The preceding perspectives on the use of language for effecting change in organizations have been useful, each in its own way. Despite their important differences on how they view language, their common emphasis has tended, in varying degrees, to be *analytical*, namely to provide a set of conceptual tools for dissecting a process, rather than suggest ways of delving *into* the process – noticing not only the words used, but, also, their place in a sequence of utterances, the intonation, the extraverbal conditions within which utterances unfold, as well as what different utterances accomplish in the temporal unfolding of a conversation. It is viewing language *from within* as active participants rather than from outside as observers and facilitators that is missing, in varying degrees, in the preceding accounts.

Argyris, for example, highlights the importance of cognitive re-programming through the use of scenario-based case studies focusing on experienced problems, written by participants who want to become productive reasoners. This is not very different from the drawing of figures and the writing of letters by the change agent, based on participants' stories, on which participants then reflect and further discuss, as advocated by narrative therapy proponents (Barry, 1997). In both cases, the idea is to effect change through intervening into or facilitating a process of either cognitive or discursive change by making it possible for people to reflect on their own and others' represented actions, hypothetical or real, under the guidance of a change agent. However, the actual process of *how* the unfolding of particular, situated, real-time conversations may lead to change remains elusive. Similarly, for all the usefulness of becoming aware of the different types of conversations in bringing about change, the conversational flow is more than the use of different speech acts in each type of conversation. It is also about 'the particular way in which we voice our utterances, shape and intone them in responsive accord with our circumstances that give our utterances their unique, once-occurrent meanings' (Shotter and Cunliffe, 2003: 17). In real life, verbal discourse is indissolubly associated with the extraverbal situation within which it emerges (Volosinov, 1987: 98). There is more in the use of language than uttering words.

We need, therefore, to move beyond an analytical approach to an 'ecological' approach (Toulmin, 1990: 175–209) that is sensitive to the particular, the local, and the timely; alerts us to the incessant creation of novelty by sentient, embodied, situated, reflexive, and responsive beings; and emphasizes both the open-endedness of processes and human praxis to shape them. In the switch from an analytical to an ecological approach we switch from a mode of inquiry based on what goes on *inside people* to an inquiry focused on what people go on *inside of*. For, as we shall see below, in an ecological approach, our surroundings must be accounted as 'determining surroundings' (Volosinov, 1987: 86; Shotter, 2009), in the sense that they exert 'calls' upon us to act *responsively* in relation to them in 'fitting' ways.

To shift from an analytical to an ecological approach, requires that we 'complicate' ourselves (Weick, 1979: 261), namely that we learn not some special, new and complex theories, even theories that pay serious attention to language, but change our *orientation* – change the way(s) of relating ourselves both to ourselves and to the others and othernesses around us. Our task then is to notice – attend to – *possible relations* that we can sense as existing within and between events that we have not previously noticed (Weick, 2007). Furthermore, we must intertwine the noticing of new possibilities in with forms of *indicative* talk that are suggestive of novel 'next steps' that we might take in our (inter)actions. Thus, instead of trying to formulate any new complex organizational theories or theories of complexity in organizations, we shall instead, following Wittgenstein (1953), take a much more *practical* approach. Our aim in this chapter will, thus, be to show how, by working *from within* an ecological approach and the complex styles of praxis to which it can give rise (Tsoukas and Hatch, 2001), quite simple talk, using ordinary, everyday words, with a minimum of technical terms, can be used to effect and to sustain innovative changes in organizational practices. That is, if such utterances are *voiced* at appropriate moments in a precise relation to shared events in shared situations, something novel may occur. Small, seemingly insignificant events can be the harbingers of big changes.

The chapter is organized as follows. Below we explain why a shift from an analytical to an ecological account of change – that is, viewing change from within – is important and what questions an ecological account would need to address. In the subsequent section we describe the importance of moments of common reference created between interlocutors. Such moments join individuals as co-participants in a situation and give their inter-actions a common orientation. This is followed by the central part of our argument, namely that at each dialogical moment there is *always unfinished openness* available, which may be characterized in terms of an *already specified further specifiability.* Put simply, co-participants in a dialogue form both *transitory understandings* of where the discussion has got to so far and certain *action-guiding anticipations* as to where it might go next. Individuals' utterances work to *specify* a shared situation into a set of distinctions while constrained by the interactive frame hitherto established – their utterances unfold in terms of their making a sequence of *similar* distinctions. A dialogically-structured event is open to further specification in an already specified manner. The change that may be brought about through re-orientation by simple, ordinary language is illustrated with a dialogue between a researcher and an IT manager. The chapter concludes with a discussion in which a brief juxtaposition is made between the 'social poetics' inspired by the ecological approach and the narrative analysis often encountered in perspectives that take language seriously, and some thoughts are offered on the need for, and significance of, a science of singularities.

HOW CAN WE THINK ECOLOGICALLY ABOUT LANGUAGE-BASED CHANGE?

There are at least two ways in which one might respond to Toulmin's (1990) call for 'the ecological style' of thinking, namely the call for paying attention to the particular, the local, and the timely. One way is to try to produce better explanatory theory from a position *outside* the phenomena in question, by drawing on complexity science: by modeling organizations as, for example, complex adaptive systems one aims at showing the mechanisms underlying the emergence of particular organizational phenomena (Holland, 1995; Miller and Page, 2007). A second, less well traveled way, aims at working *from within* a relevant phenomenon to understand more our 'way about' within it (Wittgenstein, 1953, no. 123). If the first way is ideal for the study of complex natural systems, the latter is more suited to the study of social interaction.

Let us explore the difference between these two ways. The so-called *butterfly effect* – the idea that a butterfly's flapping wings can, by causing small changes in the initial conditions of a system, initiate a sequence of events leading to large-scale changes in the system – is now well-known (Gleik, 1987). In support of what we have suggested above, namely that simple everyday talk when used at appropriate moments in relation to shared events in shared circumstances can initial great changes, we could appeal to 'the butterfly effect' to *justify* our claim that simple talk is all that is needed to navigate complex events, and to provide a vocabulary of technical terms to *explain* how such events are possible. However, such justificatory and explanatory talk is *after the fact* and *beside the point.*

It is 'after the fact' because, as is already apparent, the appeal rests on people's ability to see an event A *as* having similarities to another event B, namely seeing the claim that 'small changes in words used have big effects in organizational practices' *as similar to* the butterfly effect. Such a perception, however, is only possible with already *completed* events, so that one may say that an already well-known way of *cognizing* event A might be useful in cognizing event B. But with unfinished, incomplete events, who can say whether the similarity will hold or not? Such a way of proceeding with our inquiries is also 'beside the point', in that no matter how well we might justify and explain our appeal to the butterfly effect for our claim (that simple changes in talk can lead to large changes in an organization), such a claim will only enable us to *represent* (or picture) the circumstance, and as we are all too well aware, representations do not provide us with *actionable* knowledge; they still need interpreting (Taylor, 1985). Thus, rather than trying to produce yet more *explanatory* theories (only now theories of an ecological cast that embrace complexity), the *sui generis* character of the human world (Castoriadis, 2007), namely that it is constituted by language-based evaluative distinctions, established, reproduced and changed in the context of social practices (Tsoukas, 2009b), requires an emic approach, that is working *from within* the actual practices in question, to take better notice of crucial events and distinctions that often pass us by unnoticed.

Note the following two remarks made by Wittgenstein. First: 'The origin and primitive form of the language game is a reaction; only from this can more complicated forms develop. Language – I want to say – is a refinement, 'in the beginning was the deed [Goethe]' (Wittgenstein, 1980: 31). And the second: 'But what is the word "primitive" meant to say here? Presumably that this sort of behavior is *pre-linguistic*: that a language-game is based *on it*, that it is the prototype of a way of thinking and not the result of thought' (Wittgenstein, 1981: no. 541). In the first remark, Wittgenstein is emphasizing the importance for us of events that 'strike' us, that 'touch' us, that capture our attention in some way – 'in the beginning was the deed'. For, given how much passes us by unnoticed, such events must be of some possible importance to us. Indeed, it is important to note the foundational importance of events that are in some sense *unanticipated*, *unexpected*, or *surprising* to us, for it is such events that can be the flapping butterfly wings of change in organizations and human practices at large. Indeed, this is the point in his second remark: new thinking does not come from old thinking; it begins with events that 'touch' us in some way. But in what way? What does this mean for what we, as *insiders*, should do on finding such events *happening* to us?

The *point* of Wittgenstein's remarks is that they can work to direct our attention toward important, but mostly unnoticed, aspects of our everyday interactions with each other and with events in our surroundings. Indeed, in claiming that the *voicing* of quite simple words (such as 'Stop!' 'Look!' 'Listen!', etc.) can have crucial effects in changing people's ways of relating themselves both to their surroundings and to each other, we are not focusing on their *content*, on what we might call their *referential-representational* meaning – words that can convey a 'picture' to us of a situation not actually present to us, words that influence how we think *about* a situation. Instead, we are concerned with what we might call, following Bakhtin (1986), the *relationally-responsive* use of utterances, namely with how people spontaneously orient or relate themselves to events occurring around them.

Volosinov (1987) gives a suggestive example of the depth of what can be heard in the utterance of even a single word, and the character of what, *relationally*, it can achieve.[2] In the situation he describes, there are two people sitting in a room. Both are silent. Then one of them says, '*Well*!' in a strongly intonated voice. The other does not respond. As Volosinov notes, for us, as outsiders, this entire 'conversation' is utterly opaque. Taken in isolation, the utterance 'Well!' is empty and unintelligible. Yet, for the two people involved, this single expressively intoned word makes perfect sense; it is a fully meaningful and complete utterance. How can this be?

The utterance cannot be understood apart from the extraverbal situation in which it occurs. The verbal discourse merges indissolubly with the extraverbal situation. The latter consists of three elements: (a) the common spatial setting of the interlocutors, (b) the common understanding of the situation by them, and (c) their common evaluation of the situation. For example, in this case, at the time the utterance took place, the two *Russians* involved, *looked up* at the window and *saw* that it had begun to snow (common spatial setting); *both knew* that it was already May and that it was high time for spring to come (common knowledge of the situation); finally, *both* were *sick and tired* of the protracted winter – *they both were looking forward* to the spring and *both were bitterly disappointed* by the late snowfall (common evaluation of the situation). As Volosinov (1987: 99) notes:

> On the 'jointly seen' (snowflakes outside the window), 'jointly known' (time of year – May) and 'unanimously evaluated' (winter wearied of, spring looked forward to) – on all this the utterance *directly depends*, all this is seized in its actual living import – is its very sustenance. And yet all this remains without verbal specification or articulation. The snowflakes remain outside the window; the date, on the page of the calendar; the evaluation, in the psyche of the speaker; and nevertheless, all this is *assumed* in the word *well*. (italics in the original)

But what is the point of '*Well!*', what is achieved in its voicing? It is obvious that it does not at all reflect, accurately describe, or *represent* the extraverbal situation confronting the two Russians. Nevertheless, it achieves something of great importance. As Volosinov (1987: 100) so rightly remarks, the utterance here '*resolves the situation,* bringing it to an *evaluative conclusion*, as it were' and, in so doing, it 'joins the participants in the situation together as *co-participants* who know, understand, and evaluate the situation in like manner' (*op. cit*., italics in the original). In other words, rather than achieving something representational (i.e. describing an external state of affairs) in each of the individuals separately, the utterance achieves something bodily and relational in both together; it works to create a shared *orientation* toward their shared situation – a moment of common reference. Both now know that they feel the same in relation to the situation; they *share* it, and to this extent, they can share various expectations of each other regarding each other's actions in their shared situation.

Thus, far from the extraverbal situation being merely the external cause of the utterance – by, say, exerting an impact on the speaker – it 'enters into the utterance', says Volosinov (1987: 100), 'as an essential constitutive part of the structure of its import'. It enters it, in influencing the *intonational contour* in the voicing of the word 'Well!'. Indeed, the speaker could almost equally as well have uttered not a word at all, but simply an 'Ughh!' In other words, what is noteworthy here is that the influence of the utterance is an influence exerted not in the form of a *pattern of spoken words* but in the unfolding temporal contours of *words in their speaking* – the particular *activity* of communicating. Understanding the meaning of a particular utterance is not recognizing its self-identity but its 'specific variability' (Volosinov, 1986: 69) – its adaptability to a particular situation; a variability manifested in the unique contours of an utterance as it responsively unfolds in time. As Volosinov (1986: 68) remarks, 'the task of understanding does not basically amount to recognizing the form used, but rather to understanding it in a particular, concrete context, to understanding its meaning in a particular utterance, i.e. it amounts to understanding its novelty and not recognizing its identity'.

To sum up, by the intoned utterance of one little word by one of the two people in a shared situation, the two people involved in the *moment of common reference* so created, became meaningfully inter-related as co-participants in a situation that they both know, understand and evaluate in the same way. As a result, both came to entertain similar expectations of each other, and, to an extent, to gain a readiness to respond to each other's further actions in that situation. This was not done by one *representing* the situation to the other – for the word 'Well!' pictured nothing. It was done by what was *expressed* in the utterance's situated uniqueness, i.e. in what was expressed in the unfolding, specific context of its utterance. In other words, small and very subtle variations in an otherwise well-defined word were responsible for the quite specific and complex outcome resulting from this simple exchange.

LIVING EXPRESSION AND THE ALWAYS UNFINISHED OPENNESS OF DIALOGICAL INTERACTION

If the representational view of language fails to account for the expressive responsiveness of simple utterances, where else can we turn for guidance? This is where bodily events occurring between and within *insiders* to an interaction become crucial. Let us begin to approach this issue by first turning to the special nature of the *spontaneous, living expressive-responsiveness* of our living bodies.

There is something very special about living *expression*, something that makes it very different from the mere locomotive movement of things and objects in space, from their merely taking up different positions in space in different instants in time (Whitehead, 1925). An important difference is that while we can study already completed, dead forms (even linguistic forms) at a distance, seeking to understand the pattern of *past* events that caused them to come into existence, we can enter into a *relationship* with a living (especially human) form and, in making ourselves open to its movements, find ourselves spontaneously responding to it. It is only from within our involvements with other living forms that this kind of meaningful, responsive understanding becomes available to us. Moreover, there is a distinctive 'inner dynamic' to living wholes not manifested in dead, mechanical assemblages, such that the earlier phases of an unfolding activity of a living whole are indicative of at least the *style* of what is to come later – we can thus respond to activities in an *anticipatory* fashion.

Bakhtin (1986: 69) expresses this with respect to language as follows:

> All real and integral understanding is actively responsive. [...] And the speaker himself is oriented precisely toward such an actively responsive understanding. He does not *expect* passive understanding that, so to speak, only duplicates his or her own idea in someone else's mind. [...] Rather, the speaker talks *with an expectation* of a response,

> agreement, sympathy, objection, execution, and so forth […]. (our italics)

Thus, among the other features of such responsive talk, is not only its orientation toward the future, but its capacity to arouse in listeners (and in speakers themselves) specific *expectations* as to a next step:

> The word in living conversation is directly, blatantly, oriented toward a future answer-word; it provokes an answer, anticipates it and structures itself in the answer's direction. Forming itself in an atmosphere of the already spoken, the word is at the same time determined by *that which has not yet been said but which is needed and in fact anticipated by the answering word*. Such is the situation of any living dialogue. (Bakhtin, 1981: 280, our italics)

A good example of this process is the dialogue between the Chairman of the US House of Representatives Committee on Oversight and Government Reform Henry Waxman and the former Chairman of the Federal Reserve Bank Alan Greenspan, following the summoning of the latter to the Committee on 23 October 2008, in the immediate aftermath of the extraordinary world-wide financial crisis. Chairman Waxman started asking, somewhat hesitantly as if formulating his thoughts while speaking: 'Did you find a flaw in the reality … '. *Anticipating* the direction of the question, Greenspan stepped in, before Waxman completed his question: '… flaw in the model that I perceived as the critical functioning structure that defines how the world works, so to speak?', Greenspan said, half descriptively, half questioningly. In his immediate turn, Waxman sensing the *style* of the possible answer Greenspan would give, summed it himself up as follows: 'In other words, you found that your view of the world, your ideology, was not right; it was not working'. 'Precisely', replied Greenspan. In an interesting sequence of anticipations, we have here the answerer voicing the question and the questioner articulating the answer.

The arousal of such expectations and anticipations by our utterances is important. For Bakhtin (1986), the utterance is the *real unit* of speech communication, of language-in-use. It has a clear beginning and end, with boundaries being delimited by the change of speakers (Bakhtin, 1986: 71–72). In dialogical interaction, speakers, seeking to express what matters to them, speak such in a way that, as they utter each phrase, they arouse within themselves (and their listeners) an *anticipatory* sense of what is next needed to contribute toward the completion of their utterance.[3] They thus continue to speak, with each new phase of their utterance sensibly connected with previous phases, until that sense of completion is achieved – this is the silent *dixit* ('I have said') that listeners then take as their cue to speak. And listeners wait until they have that sense of having understood what it is that a speaker is trying to express. They then speak, but they do so now from a different point of view, and as a consequence, they can say what is unavailable to previous speakers from their point of view, and so on, often to the surprise of previous speakers, who feel that they have said all that there is to say on a particular topic.

Dialogical interaction involves three logical steps: interlocutor X, having made utterance x, has access to interlocutor Y through her receiving utterance y; Y knows how y fits with x by X uttering a new statement x' (Markova, 1987: 294–295; Tsoukas, 2009b). What this implies is that while people may know what they mean to say or what they meant, what they do not know is their listeners' 'take' on their utterance. In other words, an individual cannot know the meaning of his utterance until another individual has responded; the meaning of an utterance is dependent on the flow of the subsequent conversation. An utterance has the potential to mean, but contains no meaning in itself; its potential is realized through another's response (Gergen et al., 2004: 12). As Bakhtin (1986: 170) realized, there is open-endedness in dialogue that can never be closed:

> There is neither a first nor a last word and there are no limits to the dialogic context (it extends

into the boundless past and the boundless future). Even *past* meanings [...] can never be stable (finalized, ended once and for all) […]. At any moment in the development of the dialogue there are immense, boundless masses of forgotten contextual meanings. […].

Thus, within a dialogic approach, there are countless ways in which we might relate our language to our world. There is always something more that can be said in relation to any particular topic under discussion. There is always an *emergent* aspect to all our living, utterance-laden interactions. Nothing is ever simply repeated, nothing is ever wholly finished, there is always something uniquely novel in all of our activities. No purely pictorial or spatialized account of our interactions can capture the nature of these emergent entities. It is the characterization of this *always unfinished openness* that presents us – as theorists! – with such great difficulties.[4] We are continually tempted to complete or to close the openness in some specific fashion, and as a consequence to eliminate the very aspect of it that, as we shall see, can arouse in us *action-guiding anticipations*. How might we characterize it then, without losing its essentially always unfinished nature?

From an ecological viewpoint an utterance can be viewed as making a sequence of differences, or drawing distinctions, as it unfolds in time, within the larger contextual situation shared by all co-participants in a dialogically-structured exchange. If the situation is a practical one, then each aspect of the utterance has its import in what it 'points' to in that shared situation – its use will be to direct people's attention outwards, towards features in their surroundings of importance to them all. Thus, in any one moment, we can think of individuals' utterances as having worked to *specify* a shared situation into a set of distinctions, i.e. topics of concern (Weick, 1979). When viewed retrospectively such distinctions appear as *outcomes* of this process. However, when viewed prospectively, such topics of concern will clearly still be open to further specification, namely to making further distinctions.

But, and this is really important, if the dialogue is ever to reach a final point of agreement, then all further differences or distinctions within a topic of concern must be made in terms *similar* to those already made, unless co-participants agree 'to look at the issue in question in another way'. For example, in the relevant dialogical context of the Congressional hearing, for the dialogue to move on, Greenspan should not respond to Waxman, not at least without further comment, with a treatise on the epistemological basis of human perception and cognitive modeling. When viewed prospectively, it is not just that such topics of concern are further specifiable; it is that *they are further specifiable only in an already specified manner* (Shotter, 1984: 184). The utterance unfolds in terms of its making a sequence of *similar* differences. Interlocutors in a dialogue gradually establish an interactive frame, which constrains further contributions – subsequent utterances must fit into the frame that has already been created *and*, at the same time, develop it further (Sawyer, 1999: 455–456).

In other words, the always unfinished openness available to co-participants at each dialogical moment in their living exchanges with each other, is not just any old openness; it is an openness of a very particular kind with its own specific 'requirements' and 'callings'; it cannot just be acted into in just any way co-participants please. As Gendlin (1991) has argued, it is Wittgenstein's (1953) achievement to have shown that, because the word used for a concept is *not used in the same way* in all the different contexts of its use, there is *something else beyond our concepts* that guides us in their appropriate application. That felt bodily sense that guides us in our appropriate use of words, although still open to further specification, is, as Gendlin (1991) shows, very precise. He calls it 'the intricacy', and in his work he brings its nature into rational visibility by exploring its functioning in a range of different situations.

As speakers utter each word in an utterance, they not only specify an aspect of what is referred to in their utterance; they also arouse within themselves (and their listeners) an anticipatory sense of what is next needed to contribute toward the completion of their utterance. In other words, an utterance at any one moment manifests both its meaning so far *and* the means for its own continuation. In this sense, the production of an utterance is not especially different in character from the growth of a plant. Think here, say, of a plant growing from a seed: as a seedling, it works as a structured means mediating the further growth of the plant. And just as it cannot be predicted how many leaves and blossoms a plant might have, because that is a matter of changeable local contingencies as the plant grows into the kind of plant it is, so the development of a living utterance cannot be predicted, though its *style* is such that only certain progressions can fit and be appropriate to it.

In other words, as our everyday experience confirms (think of the Greenspan–Waxman dialogue), we do not have to wait for speakers to complete their utterances before we can understand their speech sufficiently to respond to it in practice. Indeed, often with a slow speaker we cannot resist completing their utterances for them. For present to us, in our spontaneous bodily responsiveness to their voicing of their utterances as they unfold, are *action-guiding anticipations* of what they might possibly say next. Indeed, as Bakhtin (1986) notes:

> The utterance is related not only to preceding, but also to subsequent links in the chain of speech communication ... [F]rom the very beginning, the utterance is constructed while taking into account possible responsive reactions, for whose sake, in essence, it is actually created ... From the very beginning, the speaker expects a response from them, an active responsive understanding. The entire utterance is constructed, as it were, in anticipation of encountering this response. (p. 94)

And all these *relationally-responsive*, 'transitory understandings' along with the *action guiding anticipations* associated with them, happen spontaneously within us, as a result no doubt of the countless hours of training we have had in our prior involvements in our culture.[5] We do not have to 'work them out', self-consciously and deliberately.

To sum up, we have seen that the earlier stages of the living activities of a single human being are such that, if we can be in living contact with them, they can arouse in us feelings of anticipation as to what next is likely to occur. And further, as a human utterance unfolds in terms of it making a sequence of similar distinctions, we can arrive at a sense of it having achieved its 'point' insofar as it has worked to draw attention to the aspect of the shared situation under discussion intended by a speaker. When this occurs, listeners cease to anticipate the speaker continuing their utterance any further. But, from their point of view, they can see something else that the speaker does not see. There is always something more to say. And so the discussion continues, with co-participants working with a *transitory understanding* of where the discussion has got to so far, and also with certain *action-guiding anticipations* as to where it might go next. Indeed, there is always a special kind of *always unfinished openness* available at each dialogical moment in all dialogues, an openness that we can characterize in terms of an *already specified further specifiability* – an openness that, as Bakhtin (1986) indicates, can never be finalized.

SIMPLE TALK, COMPLEX THOUGHT: AN EXAMPLE

To illustrate how simple talk can generate substantial change in an organizational setting, consider the example below (modified from an actual transcript).

Tony is a new IT executive reflecting rather despondently on his first 15 days in COMP, a large, global company. A researcher asks Tony questions and makes one suggestion. Here is the transcript of their dialogue:

Tony: We're not professional here in the way we do stuff, so there is a real opportunity to make a difference.
Researcher: *What has been striking you that epitomizes where the issues and the opportunities are?*
Tony: What's really struck me is that I tell people in COMP how other companies use good ways of doing things, and they will listen and debate and argue the pros and cons, but they have no capacity for execution.
Researcher: *What do they come up against that you have touched yourself?*
Tony: We've got barriers up between us – you know – you worry about your performance contract and I'll worry about mine. We won, and that business unit lost. But together we're all actually losing. Pockets of this going on everywhere. We've no way of operating across our activities.
Researcher: *Can you give me a specific instance?*
Tony: This very day, on day 15, I encountered it. We are trying to deliver cost savings to the CEO and VP-IT. We said: 'We are going to reduce the amount of money we spend on IT'. And they said: 'Over our dead body! You can't do that to us. We need this technology to meet our business plans so we're going to spend what we said we are going to spend and you guys can't tell us anything different'.
Researcher: *So how do you move things on? Could you, perhaps, say: 'What we are looking for is an honest, frank account of what this is actually going to take.* This (!) *is how we are going to find this difficult.* This (!) *is what it looks like when it starts to move. As it begins to move* this (!) *is what we will feel like, but* this (!) *is what we will begin to reap?' Not generalisations but real stories, real vignettes, when people in the room go* … (?) … (her intonation offers an invitation to Tony to finish her utterance).
Tony: … I GET IT!

Notice that in her very first question, the researcher – in a way reminiscent of the importance of Bateson's (1973: 285) remark about 'a difference that makes a difference'[6] – asks Tony to bring to attention something of importance that had 'struck' or 'touched' him, something of relevance to his task in COMP, something that he had not expected or anticipated, that had surprised him. Tony responds, and the researcher's second question – *What do they come up against that you have touched yourself?* – is (1) both *in response to* how Tony's utterance has 'touched' her, and (2) offering Tony an 'invitation' to go further into his own lived experience. He does, but instead of talking *with* it to express something concrete and particular, he talks *about* it in *abstract*, *general*, and *metaphorical* terms – terms which, if a listener is to act, require *interpretation*. The researcher then asks a further question to *orient* Tony toward giving a specific instance. He does. But now, instead of his previous 'state of mind' – i.e., thinking 'in his head' of the 'problem' he faces – he is back, to an extent, re-living a typical circumstance in which he encounters the 'barriers' that he had spoken of abstractly before. He thus moves from the realm of ideas, the realm of abstract things that one tries to think about changing by making 'interventions' of some kind or other,[7] into the realm of people responding to each other's utterances. Or, to put it another way, he shifts from describing relevant experiences in terms of their finished outcomes to describing an actual, particular experience in terms of its step-by-step unfolding (Weick, 1979: 195–204).

This gets him ready, i.e. orients him, both toward responding to the researcher's third question, and toward seeing *the point* of her suggestions regarding utterances he might make. So, when she says: '*Not generalizations but real stories, real vignettes, when people in the room go...,*' while leaving the ending of her utterance dangling so that he can finish it, he 'gets it'. He now sees a possibility in the situation that he had not seen before. He 'gets' the *point* that she has been trying to make with him: that a certain kind of talk, simple non-technical talk involving the telling of stories, of short vignettes, can make the kind of difference in the situation that matters to him – the breaking down of barriers between the business units – and that it is the *orientation* toward a detailing of the actual, living expressions used by those involved in the unfolding of a difficult situation that helps Tony to create within himself a *felt sense* of its unfolding movement. It is *this* – occurrences of a *felt* kind – that is crucial to the happening of institutional and organizational change.

This example shows how talk of a simple kind can work not by giving people some new information that required some new action from them, but by giving them a specific *orientation* toward something they already know, a new way of relating themselves to it, of seeing it in a certain light.[8] Thus, as a result of the researcher's questioning, Tony first orients himself toward the unexpected practicalities of the new situation he confronted in COMP; and then he realizes that the way to 'go on' within those practicalities is not to think of manipulations and interventions, but to think in terms of telling stories, providing vignettes, that may have the effect of 'touching' or 'moving' people to see things differently. Indeed, after a few simple exchanges, Tony 'gets it' – that is, he realizes that his task is not one of persuasion by argument, or to inspire by exhortation, but to do what he himself has just experienced: create the 'determining surroundings' of a meeting with business unit leaders in such a way that they also 'get it'.

DISCUSSION: POETIC METHODS AND A SCIENCE OF SINGULARITIES

Organizations may be replete with regularities, largely brought about by routines, but, as Feldman and Pentland (2003) have perceptively shown, organizational routines are filled with situational uniqueness and change every time they are put into action. The situational and the unique always emerge in human inter-action. Complexity-science, especially ecological, imagery makes us sensitive to the emergent features of human activities, arising from relationality, contextual specificity, and reflexivity. Once we adopt an ecological attitude towards human interaction in organizations, everything changes: nothing exists as the thing it is for us, except in terms of its *relations* to surroundings. Central to our ecological account has been a focus on the *expressive-responsiveness* of living forms, both to each other and to the othernesses in their surroundings, and on *their* own particular and unique ways of coming-into-Being. An ecological approach goes beyond social constructionist approaches to language-based change, and the discursive-cum-narrative methods of inquiry they have inspired, insofar as it focuses on utterances as they unfold in the context of living conversations between human beings and the spontaneous, responsive understandings they entail. An ecological approach leads to a practice of 'social poetics' (Katz and Shotter, 1996), whereby a relational attitude to a human being's use of words is encouraged, seeking to 'move' people toward a new way of relating to their practice and re-visioning their circumstances. It is not a discursive or narrative analysis of a pattern of spoken words that is sought after their utterance, but the creation of a felt, spontaneous, embodied responsiveness to words in their speaking.

Whereas narrative and discursive analysis takes as its object of investigation stories and conversations, which it seeks to analyze retrospectively as completed entities (Riessman, 1993; Pentland, 1999; Boje, 2001; Fairhurst and Cooren, 2004), hence its focus is on analyzing patterns of already spoken words, social poetics focuses instead on how embodied, responsive human beings talk from within a particular, ongoing dialogical interaction. Stories are told (and as we indicated in our illustration, must be told) in such living dialogical interactions. However, stories now are no mere objects of retrospective analysis, but openings to interlocutors' worlds that point – gesture – towards different relational possibilities in real time (Katz and Shotter, 1996: 925; Shotter, 2009). An ecological approach such as the one suggested here draws on narrative and discursive analysis to make people aware of the epistemic importance of their stories and recognizes the importance of narrative reasoning for appreciating context, motives, voices, and temporality (Tsoukas and Hatch, 2001). But an ecological approach goes further in being particularly sensitive to 'articulating a practice from within' (Shotter and Katz, 1996) by creating a living relationship in which people as embodied agents are continuously, responsively reacting to each other. Viewed 'poetically' (as opposed to merely discursively), language does things, gestures, 'brings to life new ways of "pointing beyond" our immediate circumstances, to make new connections and relations with our surroundings' (Katz and Shotter, 1996: 926).

We have argued in this chapter that innovative change in organizations is achieved not so much through theoretically driven or strategically planned interventions, by inspiring exhortations, or convincing persuasion, as through the instructive use of simple, ordinary language. To put it in a nutshell, whereas the analytical-representational (intellectualist) account views new thinking to come out of old thinking through persuasion, cognitive or, discursive re-programming, or strategic interventions, from the relational-responsive perspective adopted here, new thinking emerges from certain events that unsettle old ways of thinking and move individuals to start noticing new possibilities.

More specifically, change occurs as the result of 'poetic' events that 'touch', 'move', or 'strike' those in a group of people, events that people respond to spontaneously, in a bodily manner, events that make people feel something (even if at first 'they know not what'). Some events do have a 'big bang' character (such as the anti-communist revolutions of 1989, the 9/11 terrorist attack, and the near meltdown of the global financial system in 2008), but they need not. Small-scale events can also be very powerful for the way individuals view their common situation. Something unexpected, unanticipated, such as, for example, a colleague, a boss or a consultant using simple language *orients* us in different way to our surroundings and new, previously unnoticed possibilities are shown up. Such events function as moments of common reference, even if the people comprising the group are not all in face-to-face contact with each other, or experience the 'touching' events at different times. (As children, we were 'touched' in this way by our parents, in the games they played with us, in the stories they told us). These moments turn out to be rather complicated: it is possible to find the repetition of what already exists with them, but it is also possible to find *novel* aspects produced in our spontaneous, living responsiveness to the particularities of the current situation that we are actually in. Noticing these aspects, however, is not easy. Even when the relevant novel aspects have been made explicit, these must be accounted only as 'new beginnings', as 'new possibilities'; there is still further work to do in exploring their implications in practice; they need 'agreed formulations'. But at least, these new beginnings are genuine; they do not mysteriously lead us back into the old ideas that went into our more deliberately formulated plans and strategies. Common reference points orient people toward their common situation in a like manner, namely they are joined together as *co-participants* in a situation, which they *know*, *understand*, and *evaluate* in the same way. In moments of *common reference* all involved have noticed the occurrence of a certain event, have been touched or moved by an occurrence out in the world they all share.

A pivotal distinction on which this account rests is the distinction between two kinds of difficulty: difficulties of the intellect and difficulties of the will (i.e. of orientation or of ways of relating) (Wittgenstein, 1980: 17). We can formulate difficulties of the intellect as *problems* which, with the aid of clever theories, we can solve by the use of reasoning. Difficulties of the will, however, are quite different. For they are to do with how we *orient* ourselves bodily towards events occurring around us, how we *relate* ourselves to them, the *ways* in which we see them, hear them, experience them, value them – for it is these *ways* that determine, that 'give shape to', the lines of action we further *resolve* on carrying out. Changes in our ways of relating, in our orientation towards the others and othernesses in our surroundings, clearly, are 'deep' changes in that they are changes in our 'way' of being who and what we 'are' in the world. Hence these kinds of changes cannot be produced by following intellectually devised plans, procedures, or protocols; they cannot be done, intentionally, by people taking deliberate actions. This is because the coordinated execution of planned actions depends upon all concerned already sharing the set of existing concepts relevant to the formulation of the plan.

Central to our account here, then, is a switch away from mechanical, one-way cause and effect processes, toward a focus on the two-way *spontaneous responsivity* of living forms. As we have seen, this switch in focus entails a move away from a concern with the causal influences exerted on us by the past, toward a concern with the open-endedness of the interactions we are involved in and with how our *anticipations* of the future shape our perceptions and actions in our present circumstances. More importantly, such a switch entails a move away from a concern with the *universal* problem of our relation to our world, to a concern with understanding our *local* situation within it – hence the seemingly paradoxical idea of a *science of singularities*. The latter is a discipline, or perhaps more accurately an orientation, concerned with bringing to publicly sharable attention the fleeting, unique, 'once-occurrent event[s] of being' (Bakhtin, 1993: 2) that present novel possibilities available to us for change in our own human situations.

Our focus on singularities arises out of the recognition that such events can occur *only* in those special, two-way moments, each sensitive to its own local conditions, that we have called 'dialogical moments', for it is just in these moments that we can achieve jointly what we cannot achieve apart. As we have seen in this chapter, dialogical moments seem very different from the one-way, input–output, cause–effect moments we are used to in our more classically structured investigations. And in this sense they are special. But in another sense, they are not at all different. For, as we now realize, to the extent that, in an ecological approach, our surroundings, as 'determining surroundings', exert 'calls' upon us to act *responsively* in relation to them in 'fitting' ways, *all* our actions are, in effect *inter*-actions.

Nonetheless, we shall still insist that dialogical moments are special in that, given our naturalistic impulse to search for laws, principles, rules, and other forms of regularity in our inquiries into human affairs, they have the character of *singularities* – they are to do with unique, *once-off* novelties, moments in which *something new is created out of something given*, to paraphrase Bakhtin. The trouble is, given our everyday tendencies to talk in terms of generalities and to focus on products rather than processes, we continually try to assimilate such particularities to one or another kind of *category*, and, in so doing, we lose their creativity and their uniqueness. It is their special nature in this respect that is ignored, eradicated, even. We simply don't know how to *account* for them, for they have their existence only *within* the ongoing, unfolding dynamics of our interactions; they lack any *independent* existence in themselves. We hope this chapter has made a modest contribution in showing how we can overcome this problem.

NOTES

1 An earlier draft of this chapter was presented at the Fourth *Organization Studies* Summer Workshop on 'Embracing Complexity: Advancing Ecological Understanding in Organization Studies', 5th–7th June, 2008, Pissouri, Cyprus. We would like to thank Steve Maguire for his very helpful comments on an earlier draft.

2 Here, we are following Volosinov's text quite closely.

3 Mead (1934) describes this phenomenon well: 'That process ... of responding to one's self as another responds to it, taking part in one's own conversation with others, being aware of what one is saying and

using that awareness of what one is saying to determine what one is going to say thereafter – that is a process with which we are all familiar' (p.140).

4 As Wittgenstein (1953) remarked: 'What is most difficult here is to put this indefiniteness, correctly and unfalsified, into words' (p. 227), if you complete it you falsify it.

5 'Human learning presupposes a specific social nature and a process by which children grow into the intellectual life of those around them' (Vygotsky, 1978: 88).

6 We would like to make an addition to Bateson's phrase about *a difference that makes a difference*, and to talk of a difference that makes a difference *that matters*.

7 Interventions which, in fact, if they are to be intelligible to those to whom they are applied, must be formulated in terms of concepts already familiar to them. They thus, inevitably, result in people doing simply a variation of what is already well known to them – uniquely new changes are impossible.

8 'The problems are solved, not by giving new information, but by arranging what we have always known' (Wittgenstein, 1953: no. 109).

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20

Organisational Learning and Complexity Science: Exploring the Joint Potential

Eve Mitleton-Kelly and Ben Ramalingam

OVERVIEW

Since Cyert and March first referred to the term 'organisational learning' in 1963, the term and its application has drawn on many different theories and concepts, from transaction costs, behavioural theories, group psychology, organisational development, systems thinking, and most recently, complexity science. The literature on organisational learning, by the very nature of the topic, is not a pure academic pursuit. Some views do privilege an explanatory and descriptive focus, written from an academic perspective, while much is prescriptive and normative, written from the consultant-practitioner perspective.

While the academic approaches may suffer from a lack of realistic theoretical models against which to test and probe real-world examples of organisational learning, the practitioner-consultant oriented work is often inspirational, using emotive and symbolic language which often masks the problems and difficulties associated with learning. To make things more challenging, new ideas are introduced that sit alongside earlier concepts which may often be incompatible.

The chapter will attempt to clarify what is meant by organisational learning through an exploration of how organisational learning concepts have evolved over time, drawing attention to key issues and debates faced in translating these concepts into practice. At the heart of this exploration will be four contrasting theories of learning which recur throughout the OL literature and practice. These theories are behavioural theories, cognitive theories, social constructionist and gestalt learning approaches. Behavioural models date back to the work of Cyert and March (1963), the cognitive approaches have been articulated by Argyris and Schön (1978), social constructionist approaches have been developed by March and Olsen (1975) and more recent writers on learning communities (Wenger, 1998), while gestalt theories of learning have informed the work of Peter Senge in the Learning Organisation (1990) and Nonaka and Takeuchi in the Knowledge Creating Organisation (1995).

We will attempt to show how a complexity perspective can help get inside the black box of learning by providing a conceptual underpinning for the process, scope and conditions for learning, in particular showing how complexity can help re-think issues such as adaptation, alignment and equilibrium, the contrast between single and double loop learning, social connectedness and situated learning theories, as well as other elements of the OL literature. In conclusion, the chapter will attempt to lay out a future research agenda for organisational learning from a complexity theory perspective.

INTRODUCTION

Organisational learning: a brief history

The study of organisational learning (OL) can no longer be said to be in its infancy, with underlying principles that can be traced back to early classical management perspectives (Easterby and Lyles, 2005; Garratt, 1999) and over 40 years of scholarship since Cyert and March first made reference to the term (Shipton, 2006).

Organisational learning is now established in the management and organisational repertoire (Miner and Mezias, 1996; Shipton, 2006). However, in common with other areas of management practice such as performance, strategy, and leadership, a clear and comprehensive understanding of OL is hard to establish (Miller, 1996). Despite a growing volume of studies, it still remains unclear *'just what learning is, how it takes place, and when, where and why it occurs'* (Miller, 1996: 485, emphasis added).

The lack of clear answers does not reflect a lack of research, generating perspectives and viewpoints on learning. Rather, it relates to the fact that there are diverging opinions about the coherence of this body of research. Some writers have suggested that most OL scholars share at least some common ground. Garvin (1993) notes that most view organisational learning as an unfolding process linked to acquiring knowledge to improve performance. Dixon (1994) suggests that there is broad agreement that organisational learning relates to intentional or unintentional learning processes, which play out at individual, group, organisational and sectoral levels, in ways which transform an organisation, its work, and the direction it is taking (Dixon, 1994), for better or for worse.

There are those who suggest many of the definitions of OL are complementary rather than fundamentally original or conceptually different (Matlay, 1997) and that OL research converges much more than might be expected and that is obvious at first glance (Miner and Mezias, 1996).

In contrast, there are others who point to a distinct lack of effort among OL researchers to build cumulatively on earlier concepts and thereby developing a clear empirical focus. Instead the literature is marked by key texts, classic works, and watersheds (Rashman et al., 2008). This has led to a fragmented field, with conceptual overlap and confusion (Shrivastava, 1983; Arthur and Aimant-Smith, 2001; Snell, 2001; Ramalingam, 2005; Ramalingam, 2006; Shipton, 2006).

Others go further, and suggest that the concepts of OL are 'excessively broad, encompassing ... all organisational change ...' (Cohen and Sproul, 1991: 1) and suffer from 'various other maladies that arise from insufficient agreement among those working in the area on its key concepts and problems' (ibid.).

Some authors appear to strike a middle ground between the two extremes, suggesting that conceptual diversity can be helpful and potentially complementary (Easterby-Smith et al., 1998). Rashman and Hartley (2002), through a review of reviews, suggest there is a considerable degree of consensus on the underlying unanswered questions: 'Reviews of the literature, despite differences in approach ... find four identifiable strands:

1. the problematic nature of defining and measuring OL
2. the barriers to and enablers of such learning ...;
3. the multi-level nature of OL; and
4. the nature of knowledge creation' (Rashman and Hartley, 2002: 529)

From this perspective, while there may not be shared understanding as to what OL is, there is at least agreement as to the questions that need to be posed to develop such understanding (Ramalingam, 2005).

Part of the reason for this divergence, as will be seen in a later section, is that the theories which hypothesise how organisational learning processes work are diverse in terms of their disciplinary foundations, and the opinion on the literature will vary depending on the attention one pays to the underlying theories (Wang and Ahmed, 2002). As a concept and field of study, organisational learning represents an amalgam of influences, including individual cognitive learning, education and heuristics, adult learning, action learning, organisational development, systems theory, and human resources management. As a result of this theoretical diversity, OL literature contains a number of different, and sometimes contradictory, assumptions about the learning process, the role of individual and collective actors, the nature of organisational systems, and the way in which such systems change and adapt through learning (Ramalingam, 2005).

Also important, however, are the positions and stances of different authors on OL. This is most evident when looking at the transformations that are expected to result from learning processes. In general terms, OL consultants and practitioners have presented these transformations in prescriptive terms, focusing on improvements to organisational behaviours, when organisations attempt to become an ideal 'learning organisation'. This literature suggests a strong correlation between OL and performance (Simon, 1991). Some authors suggest that such studies dominate OL '… historically, learning articles and books have focused on general schematic models of OL, field-based qualitative insights, and simulations' (Miner and Mezias, 1996: 95).

By comparison, academics have tended to take a more explanatory, descriptive approach, which is interested in how learning happens, and how to identify the inhibiting factors (Shipton, 2006). This work is equally interested in empirical research into flawed processes of learning, which may take organisations down blind alleys, and into dysfunction or dissent. (Easterby-Smith and Lyle, 2005; Shipton, 2006)

Organisational learning is further confused by the emergence of a closely related field, that of knowledge management (KM), which is subject to its own conceptual vagaries, problems and tensions. Confusingly, many authors use the terms interchangeably, and with a wide variety of different meanings (Rashman et al., 2008). Increasingly, the two practices are seen as intertwined.

Outline and aims of the chapter

In the following section of this chapter, we seek to shed light on the diverse theoretical underpinnings of organisational learning concepts and practices. We do so by presenting different theories of learning (following Easterby-Smith et al., 1998 and Wang and Ahmed, 2002) and showing how these have, implicitly or explicitly, informed much of the organisational learning literature, from Cyert and March writing in 1963 through to Senge's Fifth Discipline and more recent works. In doing so, we take our lead from Miller, who argues that:

> Part of the problem is that learning, as portrayed in the literature, is a haphazard and eclectic notion. Researchers lump together processes that are strikingly different in their causes, effects, and domains … *we can only begin to understand learning after we have made some essential distinctions among its many varieties* …. (Miller, 1996: 485, emphasis added)

The first aim and first section of this chapter is to make such a set of essential distinctions with which to understand the OL literature. In doing so, we hope to clarify the key ideas of OL.

The second and primary aim is to review and critique these key ideas using the theoretical lens of complexity science. Previous work by the authors has identified a number of generic concepts and principles of complexity, moving towards a theory of complex social systems (Mitleton-Kelly 2003, 2004, 2006, 2007; Mitleton-Kelly and Land, 2005; Ramalingam et al., 2008).

These generic principles will be drawn upon to reflect upon a number of assumptions and concepts in the organisational learning literature. Our aim is to show how complexity principles can be used to:

- question the validity of certain OL constructs;
- reinforce existing OL concepts;
- augment OL with a more nuanced understanding; and
- suggest alternative or different ways to understand OL.

FROM LEARNING TO ORGANISATIONAL LEARNING: A THEORETICAL OVERVIEW

Four theories of learning

Easterby-Smith et al. (1999: 17) note that the '… magic juxtaposition of the terms "organisation" and "learning" stresses, rather than hides, the need for clear and elaborate conceptualisations of what is meant by both "organisations" and "learning"'. In this chapter we provide an elaboration of different learning theories, outlining a four part typology, to be used in the subsequent exploration of OL literature.

The literature on learning has wide and deep roots, in areas as diverse as educational research, cognitive behavioural sciences, psychological studies, innovation, and corporate management. Each of these areas offers a particular perspective on learning, which describes and provides a means of understanding, how individuals and groups learn. The key contribution of learning theories has been in terms of terminology and frameworks for explaining learning processes. It has been suggested that there are a number of broad categories into which different learning theories fall (Wang and Ahmed, 2002) and we look at several below.

Behaviour-based theories assume that learning is manifested by a change in behaviours shaped by the environment. In this broad set of theories, learning is the acquisition of new behaviour through a conditioning process involving proximal, repeated factors, which are central to such learning. Conditioning may be a learned reflex response, as with Pavlov's dogs, or through a system of incentives and sanctions which promote and inhibit different kinds of behaviours (Pavlov, 1927; Wolpe, 1958; Hilgard and Bower, 1966; Skinner, 1971; Nelson-Jones, 1996; Schein, 1999).

Cognitive approaches emerged as an alternative to behavioural approaches, and argue that memory and thought processes are at the heart of learning, and learning is a predominantly cerebral function, which focuses on the physiological processes of sorting and encoding information and events. As such, learning is controlled by individual learners, and not by the environment as argued by the behaviour-based theories (Bandura, 1986; Luthans, 1998).

Social constructivist approaches view learning as a process in which the learner actively constructs or builds new ideas or concepts based upon current and past knowledge or experience. Constructivist learning, therefore, is a very personal endeavour, whereby internalised concepts, rules, and general principles may consequently be applied in a practical real-world context. A key element of such approaches is that learning happens as individuals engage in talk and social activity on shared problems or tasks. Learning is seen as the process by which individuals are introduced to a culture by more skilled members (Cook and Brown, 1999).

Finally, *gestalt approaches* present a holistic approach, rejecting the mechanistic perspectives of the stimulus–response models. A 'gestalt' is an integrated whole system with enmeshed parts, with the whole being greater than the sum of the parts. At the heart of gestalt theories is the idea that 'human nature is organised into patterns or wholes, that it is experienced by the individual in these terms, and that it can only be understood as a function of the patterns of wholes of which it is made' (Perls, 1973: 5).

From a gestalt perspective, learning is not just a mechanistic response to a stimulus. It is the understanding of a structural whole, through the dynamic interaction between a focus of interest, and its context (Wang and Ahmed, 2002).

Ikehara (1999) suggests that gestalt learning happens on the 'whole' person level, is an interaction between mind and body and between individuals and their environment, and takes place at cognitive, physical, emotional and spiritual levels.

Contribution of theories of learning to organisational learning

One of the earliest literature reviews of OL suggests 'there are really no rigorous theories of organisational learning [but] there are several interesting conceptualisations of the phenomenon' (Shrivastava, 1983: 9). If this is indeed the case, it might be expected that theories of learning will play a prominent role in such conceptualisations.

This is supported by the literature itself, and by summary reviews during the past decade. Indeed, a mapping undertaken by Easterby-Smith et al. (1998) suggests different approaches to organisational learning, which correspond closely to the learning theories outlined above (the technical information processing model, the cognitive model and the social process model, are presented as key categories).

In this section, the literature on OL will be reviewed with reference to these four learning theories. Prominent examples of OL work which falls into each category will be presented, as well as any contrasts and debates evident in the literature.

Behavioural approaches to OL

A number of the principles underlying OL predate the formal use of the term in the 1960s. Learning was implicit in the scientific management approaches, as popularised by Frederick Taylor and his contemporaries. The focus of scientific management was on improving the execution of tasks or routines, in which learning was the result of analysis by a chief executive, who was then able to specify how tasks or routines should be undertaken, and then create incentives for workers to follow.

Studies often focused on a single dimension such as productivity and were criticised for their narrow focus. Single-focus models of learning were significantly broadened by the behavioural school of organisational learning. Cyert and March (1963) are widely accepted to be the first to use the term 'organisational learning'. They described firms as adaptive learning systems in which behaviour unfolds through standard operating procedures (Miner and Mezia, 1996). When performance does not meet the goals, problem-driven searches take place, which focus on retaining useful routines while discarding others. The focus here is on an incremental process of learning, which involves adjustment of goals, rules, procedures and routines in response to environmental challenges, thereby achieving greater 'alignment' with the environment, shown in Figure 20.1.

The central role of information processing in this model has been illustrated by a number of authors (Huber, 1991; Easterby-Smith et al., 1999).

Learning involves 'encoding inferences from history into routines' that are independent of individuals, guide behaviour and change in response to experimentation and search (Levitt and March, 1988: 517). Work by Moorman (1995) uses survey data to distinguish between organisational information processing patterns. Specifically, behavioural theories suggest that standard operating procedures drive organisational action, and these institutionalised forms of actions are what produce results. This process is presented as a form of trial-and-error learning (Miner and Mezias, 1996). Such approaches remain prominent today, especially in government

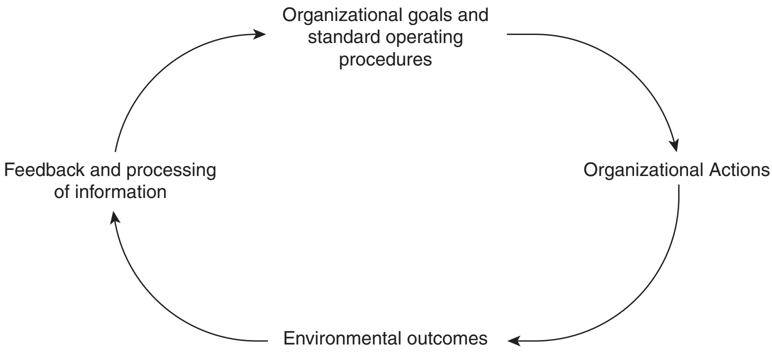

Figure 20.1 Behavioural learning model

and public sector learning; for example, Leeuw et al. (1994) define OL as the process of detecting and correcting error. More recently, Greve (2003) used a behavioural model of learning to argue for a rigorous set of quantitative measures for OL.

Cognitive approaches to OL

This approach to learning as a technical information-based incremental process has been challenged by cognitive approaches to OL. An early challenge specifically targeting the behavioural approaches of Cyert and March (Cangelosi and Dill, 1965) argued that the behavioural learning model can only be applied to stable, mature firms operating in stable environments.

As a result, behavioural approaches were not seen to be relevant to organisations working in dynamic contexts. The relationship between individual and organisational learning, inherent in the rational utility maximising approach of Cyert and March, was seen as overly simplistic. In reality, these levels of learning are characterised by tensions and problems and Cangelosi and Dill (1965) concluded that rational utility maximisation was not the fundamental underlying motivation for learning.

Cognitive approaches seek to explain learning with reference to 'mental processes from which are derived thought, belief, perception and interpretation' (DeFillippi and Ornstein, 2005: 22). Writers and practitioners in this school are concerned with knowledge structures, belief systems, and operational strategies (Argyris and Schon, 1978; Duncan and Weiss, 1979), and how these factors shape individual thinking and behaviour. Specifically, cognitive learning processes are those which result in changes to mental models held in long-term memory by creating new connections or altering existing associations between knowledge structures.

Argyris and Schon (1978), perhaps the most influential scholars working within the cognitive approach, categorise and distinguish three forms of learning, as illustrated in Figure 20.2.

They suggest that single loop learning is learning within the context of existing standard operating procedures. Such incremental learning is presented as the main focus of the behavioural theories to OL. While these may be accurate models of such learning, they do not explain the most important learning that happens in organisations. Specifically, behavioural approaches disregard both double-loop learning (i.e. the questioning of and change in assumptions, practices and policies which guide work), and triple-loop learning, which questions and adjusts the organisational paradigms, values and purposes that motivate and inspire work.

Argyris and Schon place great emphasis on the importance of double-loop learning and the empowerment of employees to challenge existing policies and actions in organisations.

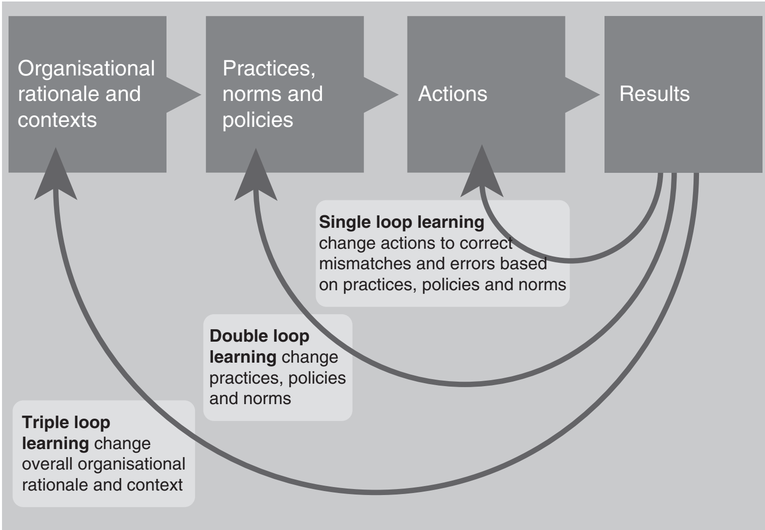

Figure 20.2 Single, double and triple loop learning. Source: Ramalingam et al. (2009).

In subsequent work, Argyris pays particular attention to the cognitive and social barriers impeding such double loop learning. He emphasises that rational utility maximisation is a rather crude way to characterise the motivations of learners in organisations. Instead, he suggests, there are a number of individual and organisational 'defensive routines', entrenched in the minds of learners, which set clear limits on both individual and social action.

Specifically, double loop learning questions the basis of and justifications for policies implemented in organisations, which often poses both potential threats and risks embarrassing managers and employers. This triggers what Argyris describes as a universal self-protective physiological mechanism which inhibits second-order learning, referring to studies done with more than 6,000 individuals from different backgrounds, races, cultures, class, age and gender. By bringing attention to the ways in which deeply entrenched reactive defensive mechanisms shape and severely constrain what a firm can learn, the cognitive approaches present a sustained critique of the rational learning models of Cyert and March.

Levitt and March (1988), also in the cognitive school, are more sceptical about the capacity of organisations to learn from past experience and to manage knowledge effectively. In a widely cited 1988 article they highlight the considerable factors that weigh against organisational learning in practice.

As a result of the importance of mental processes, the role of individual learners is central to the cognitive school. There is, however, some difference of opinion as to exactly how collective learning results from individual learning. For some authors in the cognitive approach, organisational learning is individual learning writ large, while others see organisational learning as resulting from the organisational forms, which are created by individual learners, which then facilitate further learning and organisational transformation. This contrast can be characterised as the difference between a 'macro-cognitive' approach to OL and an 'enabling environment' (Mitleton-Kelly and Land, 2005: 44) approach.

Kolb, another scholar in the cognitive school, uses a learning cycle to model how individuals learn from experience, and then extends this to the entire organisation. Building on

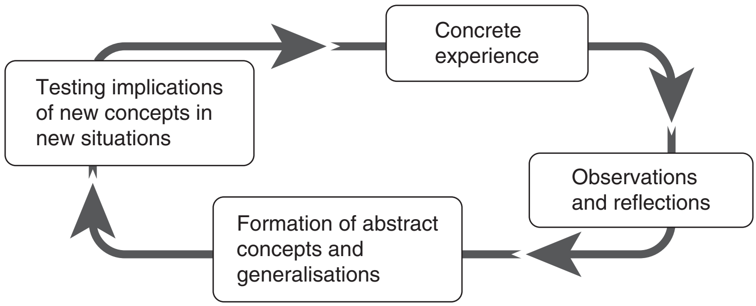

Figure 20.3 Kolb's experiential learning model. Source: Kolb (1983)

earlier work by social and educational psychologists, Kolb (1983) developed the notion of experiential learning as a four-stage cycle shown in Figure 20.3.

The Kolb model sees the process of learning as one where learners move from actor to observer, from specific involvement to general analytic detachment. Learners, if they are to be effective, need four different abilities – concrete experience, reflective observation, abstract conceptualisation and active experimentation (Kolb, 1996).

Honey and Mumford (1982) adapted this model for use by middle/senior managers in business. They hypothesised that different individuals have natural preferences for different ways of learning, and these relate to the different stages of the learning cycle. They described the four dominant types and their learning preferences as: activists, reflectors, theorists and pragmatists. From this perspective, organisational learning requires that these individual orientations are acknowledged and capitalised upon by bringing together teams which include learners with diverse preferences.

Social construction approaches to OL

The third school of organisational learning is the social construction school. This perspective, in contrast to the two models presented so far, which place individual learning at the heart of OL, explores OL as the product of social interactions.

Individuals are seen as social actors who collectively construct an understanding of what surrounds them and learn from the social interaction within organisational systems (Gherardi, 2000). This notion that learning takes place among and through people has been framed in a variety of ways in the OL literature (Elkjaer, 2004), including action learning processes and action learning sets (Revans, 1971, 1980), 'situated learning' (Brown and Duguid, 1991; Lave and Wenger, 1991; Richter, 1998); social learning (Elkjaer, 1999), practice-based learning (Gherardhi, 2000) and communities of practice (Brown and Duguid, 1991; Lave and Wenger, 1991).

According to the social construction perspective, learning can only be achieved through active participation, and as participation is constantly changing, this perspective focuses on change, rather than on order and regulations (Elkjaer, 1999).

One of the best known examples is Revans (1980) work on 'action learning sets' emphasising the need to integrate cognition and action, with theory and behaviour, while working in the context of small groups, or 'sets'. Through such learning sets, colleagues learn from each other tackling real problems at work, by paying particular attention to questioning.

This model has been extended by Dixon (1994) who uses an organisational learning cycle through which information is generated based on the direct experience of employees, which is then shared and interpreted by the group leading to responsible collective action.

Rather than attempting to understand what type of cognitive processes or conceptual structures are involved in OL, the social construction perspective sets out to explain what type of social context is most suitable for OL, focusing on the group and the community, rather than on the mind of the individual. Therefore, as Elkjaer (2004: 50) argues, learning is perceived as a continuous activity that cannot be controlled; only the context can be controlled, thus facilitating OL to a greater or lesser extent. In accordance with the social perspective, OL is conceptualised as the process of social construction of shared beliefs and meanings in which the social context plays an essential role (Berger and Luckmann, 1967).

Combined and gestalt approaches to OL

Some of the most successful approaches to organisational learning have not used one specific approach, but instead have synthesised elements considered to be complementary from different schools. For example, the behavioural and cognitive schools are brought together by Yeo in a single model of organisational learning which encompasses individual, group and organisational levels. The learning loops model of Argyris and Schon also brings these two schools together, in a single framework, although it does include a critique of approaches which focus solely on single-loop, behavioural learning. March and Olsen (1975) attempt to explore the linkages between individual and organisational learning. They do so by suggesting that individual beliefs lead to individual actions (cognitive school), which in turn may lead to organisational action and a response from the environment which may induce improved individual beliefs (behavioural school) and the cycle then repeats itself (Levitt and March, 1988).

Another example is the work of Daniel H. Kim (1993), who suggests that organisational learning takes place when implicit individual mental models (cognitive school) become explicit and are distributed more widely across a community (social construction) giving rise to shared mental models which provide a basis for collective action and collective meaning within the firm. Garvin (1993) points to five distinguishing features of learning organisations 'systematic problem solving, experimentation and testing of new knowledge, learning from experience, learning from others, and shared knowledge and knowledge-spreading mechanisms' (1993: 110).

Other attempts to synthesise the different approaches have explicitly drawn on gestalt approaches to learning to justify such integration. Perhaps the most influential gestalt approach has been the work of Peter Senge (1990), which popularised the notion of organisational learning and sparked a significant increase in the literature. The five disciplines are personal mastery, mental models, team-based learning, shared vision, and systems thinking.

Each of the first four disciplines can be seen as building on a particular intellectual tradition. Personal mastery and mental models draw from cognitive approaches, while team-based learning and shared vision draw on the social constructionist schools. These disciplines are brought together by systems thinking, the eponymous 'fifth discipline'. Senge (1990) argues that organisational learning is only successful when it is based on an understanding of how the whole organisational system is connected, rather than focusing on individual parts. Such understanding is facilitated by systems thinking approaches, which enable organisations to react better to archetypal patterns, which are manifest in the wider world. The underlying principle is how an organisation behaves differently, based on its sensing of the environment; this can be seen as an example of the behavioural school. Senge was able to bring together elements of the main learning theories into a coherent package – a clearly communicated and compelling set of ideas, presented in a way which appealed to managers, practitioners and researchers alike. The Fifth Discipline is widely acknowledged as a watershed for organisational learning, both practically and theoretically. From a gestalt perspective, however, it is suggested that the Fifth Discipline popularised some appealing but overly simplistic holistic concepts (Jackson, 2005).

More recently, the five disciplines learning organisation model, has been adapted and extended into a model of the 'practically wise organisation' (Rowley and Gibbs, 2008), with the addition of two extra 'disciplines'. Jamali et al. (2006) use the five disciplines to explore a new management paradigm for the public sector, of the post-bureaucratic organisation. Whereas in the old public management paradigm the guiding values were hierarchical line management, inward focus, cutting costs, complying with rules, and dividing labour into simple and narrowly defined tasks; post-bureaucratic management is guided instead by 'consensus decision-making, implicit control, trust, egalitarianism, and a holistic concern for people' (ibid., 2006: 339).

Another key text that also makes use of gestalt concepts is the work of Nonaka and Takeuchi (1995). An important part of The Knowledge Creating Company is devoted to the contrast between Western and Eastern ways of thinking. They argue that the Eastern view of the world is systemic (holistic, in gestalt terms) compared to the Western systematic, or reductionist, way of approaching situations. The book suggests that the latter should be abandoned in favour of a holistic view.

Nonaka and Takeuchi define knowledge creation as the result of the spiralling process of interaction between tacit knowledge (or know-how, which is hard to express, but can be demonstrated) and explicit knowledge (which can be articulated in words). They suggest that there are four key processes through which knowledge is created, namely, Socialisation, Externalisation, Combination and Internalisation (SECI).

Together, these processes make up the SECI principles, which provide a set of pointers that can be used by managers to ensure that they are facilitating effective knowledge and learning in their ongoing projects and programmes. This model is a combination of cognitive and social constructionist schools of learning. Nonaka and Takeuchi emphasise the importance of ba, a Japanese word with no literal English translation, but which is in line with the ideas of holism from gestalt theories.

THE IMPLICATIONS OF COMPLEXITY SCIENCES FOR OL

Complexity science is increasingly being seen by academics as a means of understanding organisations (Chiva, 2003) with potential relevance for OL. Mathews et al. (1999) argue that Complexity Science has the potential to extend and enhance our knowledge of organisational change and transformation processes, while Cohen and Sproul (1996) suggest that the literature on OL shows a certain affinity with the literature on complex adaptive systems. However, relatively few attempts have been made to bring these ideas, systematically and thoroughly, to bear on the OL literature (Chiva, 2003).

We will make an initial attempt to do so here, by reviewing the ideas in each of the schools of OL from a complexity perspective. In particular, we will explore the strengths and weaknesses in the OL approaches outlined above, and assess what complexity science can contribute, to deepen our understanding of OL.

Behavioural OL and complexity sciences

The behaviourist models popularised by Cyert and March focus on adaptation to an external reality which is the result of a rational, utility-maximising information process. This leads to changes in standard operating procedures and goals, to reach a better alignment with the environment. Each of these highlighted ideas is critiqued below.

Key points from complexity sciences are:

- The idea of adaptation is central to complex adaptive systems (CAS) theory (Anderson, 1999; Axelrod and Cohen, 1999). CAS are made up of interconnected agents that seek to enhance their fitness through adaptations. Adaptability is seen as a particular system's capacity to adjust to changes in the environment without endangering its essential organisation, and is therefore also related to notions of resilience and diversity (Hollings, 2001).

- Stuart Kauffman's influential work (1993, 1995) has presented the idea of an 'adaptive walk' on a fitness landscape, in which adaptive agents are moving to places of optimal fitness. From this perspective, any organisation can be seen as composed of agents that seek to maximise fitness by making adjustments in how they view and interact with other agents and the environment (Dooley et al., 2003).
- The driver of such behaviour, however, is not the rational utility-maximising search for some optimal solution, as might be inferred from the notion of 'alignment' posited by the behavioural approach to OL. First, 'any strategy can only be optimum under certain conditions, and when those conditions change, the strategy may no longer be optimal' (Mitleton-Kelly, 2003: 36). This means that the organisation needs to explore its space of possibilities, or alternative strategies, to generate a variety of responses under different environmental conditions and to work simultaneously on several distributed micro-strategies (Mitleton-Kelly, 2003: 36). Second, rather than gathering perfect information that would be necessary for utility maximising choices, in reality each agent observes and acts on local information only, derived from those other agents to which it is connected (Anderson, 1999).
- This means that organisations have a mutually adaptive or co-evolutionary relationship with their environment, such that they are not simply trying to align with a known, stable environment, but rather the organisation is learning to adapt to an environment that is itself influenced and changed by the decisions and actions of other organisations and by wider societal, technological and political changes (Anderson, 1999; Axelrod and Cohen, 1999; Boisot and Child, 1999). Stacey (1996: 36) argues that: 'As human agents and the systems they make up move around the behavioural loop of discovery, choice and action, they are clearly engaging in a co-evolutionary feedback process in which what one does affects the others and then returns to affect the first'.
- In biology, as entities and organisms interact and adapt within an ecosystem they alter 'both the fitness and the fitness landscape of the other organisms' (Kauffman 1995: 242). The way each element influences and is in turn influenced by all other related elements in an ecosystem is part of the process of co-evolution. The rate of co-evolution (McKelvey and Yuan, 2004) is another key dimension to consider (Antonacopolou and Chiva, 2007).

Cognitive approaches and complexity science

The cognitive approach suggests that individual mental processes are at the heart of organisational learning. Learning processes are seen as either writ large to the group and organisational levels, or are enhanced and supported by effective organisational structures and processes.

Key points from complexity sciences are:

- Complexity science hypothesises that social systems have underlying schemata that enable the coordination of multiple agents. Social systems reflect such schemata in their routines and practices (Axelrod and Cohen, 1999). However, in complexity, such schemata are not standard operating procedures, as posited by the behavioural OL school. Nor are they merely mental processes, as posited by the cognitive school. Rather, they are defined as 'a set of rules that reflects regularity in experiences and enables a system to determine the nature of further experience and make sense of it' (Stacey, 1996: 289). Such schemata are created by actors in an interactive relationship and provide a framework enabling agents to anticipate the results of their actions (Holland, 1995; Stacey, 1996; Anderson, 1999). In organisational systems, agents might be individuals, groups, or a coalition of groups. After scanning their environment, agents develop schemata as rules for action and interpretation. Routines and practices are schemata, that is, operating procedures which co-evolve along with the general principles governing the system. Learning occurs when there is a change in the schema; agents learn becoming more robust, more reliable while widening their adaptive features (Antonacopolou and Chiva, 2007).
- The notion of single loop learning as working within existing mental models and double loop

learning as challenging them, simplifies the reality of constantly interacting schemata, competing and evolving in a complex social system. Changes in agents' schemata, interconnection among agents, or the fitness function that agents employ produce different learning outcomes. Such learning is not amenable to management control or authority, but is in important ways, self-organised and emergent. As Chiva (2003) notes, this may be just as true for single loop learning as double loop learning.

- The relationship between individual and organisational learning is under-theorised in cognitive OL approaches; it is not just a case of OL being the sum of individual learning. According to complexity OL is not the sum of all the learning of individuals; it is the outcome of interactions between the learners (Ramalingam et al., 2008). OL is an emergent property, which is systemic and is therefore more than the sum of the parts. If we were to understand the process of emergence, we would go a long way to understanding OL. Once the emergent has been created in a micro to macro process, it also affects the interacting entities. In other words, once OL happens at the macro level, it affects individual learning and learners at the micro level. It does so in two ways: (a) it opens up new possibilities; while at the same time it (b) constrains the behaviour of the interacting individuals and their future learning (Juarrero, 2002; Kaminska-Labbe et al., 2006; Mitleton-Kelly, 2007).

Social constructionist OL and complexity

The social constructionist school, with its focus on learning as emerging from social interactions, has much in common with key complexity concepts. Complexity, however, adds a deeper understanding of the process, by providing an explanatory framework.

Key points from complexity sciences are:

- In particular, the notions of interconnectedness as a way to describe different kinds of interactivity has been used by numerous authors to suggest the different kinds of learning that might occur in an organisation or group. Complexity hypothesises not just that interactions matter for learning, but goes further to suggest that, the manner in which groups are interconnected, has a profound effect on the kinds of learning that can take place (Ramalingam et al., 2008). It suggests both going beyond a knowledge-based view of interaction and also developing a more detailed understanding of the extent to which that interaction is essential for understanding how learning takes place.
- Complexity also provides an explanation of how environments can either inhibit or enable individual learning and the contribution of individuals to the learning process. In complex systems, there are networks of relationships with different degrees of connectivity. Degree of connectivity means strength of coupling (Marion, 1999) and the dependencies known as epistatic interactions (Kauffman, 1993; Mitleton-Kelly 2003); i.e. the extent to which the fitness contribution made by one individual depends on related individuals. This is a contextual measure of dependency, of direct or indirect influence that each entity has on those it is coupled with.
- In a social context, each individual belongs to many groups and different contexts and his/her contribution in each context depends partly on the other individuals within that group and the way they relate to the individual in question. An example would be a new member joining a team. The contribution to learning, that individual will be allowed to make to that team may depend on the other members of the team and on the space they provide for such a contribution, as much as to the skills, knowledge, expertise, etc. brought by the new member (Mitleton-Kelly, 2003).
- This interdependence also helps clarify why each agent carries out a function within a particular context, which itself is defined by the agents' relationships with other agents (Holland, 1995). It is diversity of the agents that allows a social system to remain viable. Inherent heterogeneity provides the basis for renewing the system and the social conditions that allow it to function. In this model, learning emerges as a result of the conjunction of networks of varied and often conflicting individuals, groups, functions, policies, and processes (Uhl-Bien et al., 2007).
- The self-organising nature of social emergence suggests that leaders cannot directly control complex network dynamics, but rather can direct those dynamics towards learning by creating the appropriate conditions and fostering learning-oriented behaviours and activities of members (Marion and Uhl-Bien, 2001), that is,

by creating an enabling environment (Mitleton-Kelly, 2003).

- Perhaps the most comprehensive review of social learning and complexity is by McKelvey and Yuan (2004). Through the use of agent-based models, the authors seek to test a number of hypotheses related to a more dynamic form of the theory of situated learning, and to the kinds of linkages that can enable learning. The hypotheses, paraphrased, relate to how the rate and amount of group learning varies with group size and the number of interactions within a group. In particular, the notion of a 'complexity catastrophe' is shown to occur when excesses in both size and interconnections lead to excessive learning failures, as well as 'suboptimal learning adaptations'. Large groups jeopardise learning opportunities for individuals, whereas groups which are too small are unable to adequately explore the fitness landscape, therefore missing on adaptive opportunities.

The gestalt school and complexity

As with the social construction school, complexity adds to and augments the gestalt approaches, which share much common ground with complexity.

Key points from complexity science are:

- The focus on systems thinking in the gestalt school is especially interesting because of the close relationship this has with complexity science. From Senge's perspective (1990), systems' thinking focuses on seeing interrelationships rather than linear cause-effect chains, and seeing processes of change rather than snapshots. This leads to a search for certain types of systems structures that recur again and again: the deeper patterns lying behind events and details, to which an organisation can then know how to best react.
- Systems theory covers the concepts of connectivity, interdependence, feedback and emergence, but is limited to those concepts. Complexity theory builds and extends those concepts and adds new ones such as co-evolution, exploration of the space of possibilities, self-organisation, far from equilibrium, historicity and others, to provide a coherent description, of organisations as complex social systems (Mitleton-Kelly, 2003). An important difference is that, systems thinking posits the possibility that an organisation can achieve equilibrium, with the implication that OL helps an organisation achieve such a 'balanced state'. By contrast, complexity suggests that an organisation may never reach a stable equilibrium, but may move around the space of possibilities, constantly co-evolving with a changing broader environment; the implication being that OL helps to navigate the inherent uncertainty of a constantly changing environment (Ramalingam et al., 2008).
- Jamali et al. argue that in the change from a bureaucratic or a post-bureaucratic organisation, Senge's five disciplines become emergent properties arising from the interaction, combination and co-evolution of post-bureaucratic properties leading to the creation of a complex learning organisation. Emergent properties and nonlinear relationships from complexity theory are brought in to augment the five disciplines (Jamali et al., 2006).
- Stacey's (2003) complex responsive processes provide a radical re-visioning of organisations as essentially being dynamic processes of communication: 'Learning is emerging shifts in the thematic patterning of human action … Learning occurs as shifts in meaning and it is simultaneously individual and social. Learning is the activity of interdependent people and can only be understood in terms of self-organising communicative interaction and power relating in which identities are potentially transformed. Individuals cannot learn in isolation and organisations can never learn' (Stacey, 2003: 8–9).

TOWARDS A FUTURE RESEARCH AGENDA

The value of complexity, as we hope to have illustrated, is not only in helping to integrate different theoretical approaches to OL thereby providing a bridge between the behavioural, cognitive, social and gestalt approaches. Complexity science also provides an explanatory framework to help us understand OL and how to enable it.

Complexity can deepen certain concepts, challenge others, and add nuance. Moreover, it can help us develop a 'continuous' theoretical thread, which helps to move intellectually from the individual to the group and the organisational and inter-organisational levels, and presents concepts and hypotheses around how organisational learning actually happens in practice. Because the principles of complexity are scale-invariant, the emergent processes are similar from individual to group, group to organisational, and organisational to sectoral, it provides a mechanism for developing hypotheses that are integrated across the different levels.

A future research agenda would include the following:

- Identification, description and explanation of:
  - the inhibitors and enablers of OL within the context of an enabling environment;
  - how the process of learning transitions from micro to macro levels or from individual to group, organisational and inter-organisational levels.
- An explication of Miller's (1996) challenge to consider 'just what learning is, how it takes place, and when, where and why it occurs' drawing on the key principles of complexity science.
- Questioning the limitations of existing approaches.
- Challenging the validity of under-theorised OL constructs, and augmenting these with a more nuanced and evidence-based understanding.
- Exploring alternative ways to understand OL to inform practice, based on empirical research.

However, there is a challenge for both the OL and the complexity communities in taking such an agenda forward. Specifically, the question is how to move future work beyond 'interesting conceptualisations', of which there are many in the OL literature, towards systematic theories. At present, there are relatively few applications of complexity to OL, and of these few are empirically based. The challenge, then, is how to take forward this research agenda in an evidence-based and systematic manner. The OL community is a fragmented one, and lacks a common exploratory framework to draw itself together to address longstanding issues. We believe complexity science has the potential to provide this framework, by offering a common ground. OL approaches do have a natural affinity with complexity and the potential benefit to both the OL and the complexity communities of taking this shared agenda forward would be considerable.

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21

Complexity and Management: A Pluralistic View

Kurt A. Richardson

INTRODUCTION

This chapter is an attempt to explore the implications of the emerging science of complexity for the management of organizations. It is not intended as an introduction to complexity thinking, but rather an attempt to consider the 'So what?' question – the one of real importance to managers trying to do their jobs. The general message is that there is no single 'optimal' way to manage an organization and that management is – and always will be – as much an art as it is a science. In a sense complexity thinking is about limits and, specifically, about limits to what we can know about our organizations and the environment in which they operate. Because of these limits to knowledge there are, then, limits to what we can achieve in a pre-determined, planned way. This therefore implies a switch from traditional management methods to the acceptance of a 'learning' approach in which actions and decisions are part of an ongoing learning process through which our understanding and knowledge evolve as we attempt to fit experience into our changing interpretive framework of the situations we face.

The first section explores the difference between the view that organizations are complicated and the view that organizations are complex. This distinction leads to very different conclusions about what we can mean by the term 'management theory'. This first section is a little philosophical so I hope it doesn't scare anyone off! Linear (complicated) thinking is often rather superficial and simplistic, whereas nonlinear (complex) is more sophisticated and often requires more time to do properly. Complexity thinking actually requires us to spend a little more time thinking and a little less time working.

The next section presents and discusses an important concept in complexity thinking: incompressibility. It is this very notion that denies the possibility of a nice and neat theory of organization that managers might learn and execute. I'm sorry – being a good manager is always going to be a challenging job; there's no easy way out!

The penultimate section considers three schools of thinking within the complexity community followed by a brief discussion of how each school might inform management activity. Some concluding remarks will be offered to close the article, but first let's consider what we might mean by labeling an organization 'complex'.

ORGANIZATIONS: COMPLEX OR COMPLICATED?

What if human organizations were *complicated* rather than *complex*? The simple answer to this question is that the possibility of an all-embracing Theory of Management would almost certainly exist. This would make management very easy indeed as there would be a book of theory (*The Management Bible* – it would probably challenge the current all-time bestseller in sales!) that would tell the practicing manager what to do in any given context. The means of achieving effective and efficient organizational management would no longer be a mystery. But what is it about the concept of 'complicated' that makes this scenario plausible? Why has the possibility of a final management theory not been realized yet, given the millions of man-hours and published pages devoted to the search? Why does approaching organizations as 'complex' rather than 'complicated' deny us of this possibility?

A very common (but inadequate) description of a complex system is that such systems are made up of a large number of parts that interact nonlinearly.[1] But, by this definition the modern computer for example, would be a complex system. A modern computer is crammed full of transistors which all respond nonlinearly to their input(s). Despite this 'complexity' (*sic*) the average PC does not show signs of emergence or self-organization and neither gets bored nor happy; it simply processes (in a linear fashion) the instruction list (i.e. a program) given to it by its programmer. Even the language in which it is programmed is rather uninteresting. Although there are many programming languages, they can all be translated into each other with relative ease. Technically this is to say that computer languages are *commensurable* with each other. A line of code in C# can be translated into Visual Basic very easily – the one line of C# code may require more lines of VB code to achieve the same functionality but it can be done in the vast majority of cases. The universal language into which all such languages can be translated without loss is called 'logic' (more accurately, Boolean, or even binary, logic). More often though, if a programmer wants to use a language very close to the universal language of computing, *assembly* is used as this at least contains concepts that are more easily read by mere mortal programmers (although the domain knowledge – microelectronics – needed to program in assembly is a major requirement). This is then translated (without loss) into machine code (which is based on Boolean logic) – writing sophisticated programs directly in the language of the 0s and 1s of Boolean logic is nigh on impossible. The computer cannot choose the way it interprets the program, it cannot rewrite the program (unless it is programmed to in a prescribed manner), and it cannot get fed up with running programs and pop to the pub for a swift pint! So, what is it about the modern computer that prevents it from being labeled a *complex* system, but rather a *complicated* system?

The critical element is *feedback* – reflecting the strong interconnections. It is the existence of nonlinear feedback in complex systems that allows for *emergence, self-organization, adaptation, learning* and many other key concepts that have become synonymous with complexity thinking – and all the things that make management such a challenge. It is not just the existence of feedback loops that leads to complex behavior, but the interaction between them that is important. Once we have three or more *interacting* feedback loops (which may be made up from the interactions of many parts) accurately predicting the resulting behavior via standard analytical methods becomes problematic (at best) for most intents and purposes.

In a relatively simple complex system containing as few as, say, fifteen parts/components, there can be hundreds of interacting feedback loops. In such instances the only way to get a feel for the resulting dynamics is through simulation, which is why the computer (despite its rather uninteresting dynamics) has become so important in the development of complexity thinking. We say that the prediction of overall system behavior from knowledge of its parts is *intractable*. Basically, *absolute knowledge about the parts that make up a system and their interactions provides us with very little understanding indeed regarding how that system will behave overall*. Neither do we understand how the overall behavior may feedback on that of the individual elements in a multi-level dynamic. Often the only recourse we have is to sit back and watch. In a sense the term complex system refers to systems which, although we may have a deep appreciation of how they are put together (at the *microscopic* level), we may be completely ignorant of how the resulting *macroscopic* behavior comes about – i.e. complexity is about limits to knowledge, or our inevitable ignorance.

Without this understanding of causality, planning for particular outcomes is very difficult indeed. In the computer (which we will now class as a complicated system) causality is simple, i.e. low dimensional – few (interacting) feedback loops (although there are many millions of connections). In complex systems, causality is networked making it very difficult indeed, if not impossible, to untangle the contribution each causal path makes. It is hard enough to grasp the possibilities that flow from a small group of people let alone the mind-boggling possibilities that might be generated from a large multi-department organization. Maybe this is why a major part of management tends to be suppressing all these possibilities so that one individual might begin to comprehend what remains – departmentalization is an obvious example of a complexity reduction strategy.

Another unexpected property of complex systems is that there exist stable abstractions, not expressible in terms of the constituent parts, that themselves bring about properties different from those displayed by the parts. This sentence is a bit of a mouthful, but I have here succinctly described the process of emergence although in a rather awkward way. This is deliberate. More often than not emergence is portrayed as a process from which macroscopic properties ‘emerge’ from microscopic properties, i.e. the properties of the whole emerge from the properties of its parts. But this is an overly simplistic view of emergence. When recognizing the products of emergence, e.g. novel wholes, what is really happening is that we are abstracting (which essentially means information filtering, i.e. ignoring some information in favor of paying attention to some other information that comprises some kind of pattern) away from the description in terms of parts and interactions, and proposing a new description in terms of entities or concepts quite different from the constituent parts we started with – regarding an organization as a collection of interacting departments rather than a collection of individual people is the same process. What are emergent are new capabilities and functionalities of which the constituent microscopic entities are quite incapable which calls into question all theories and models cast in terms of typical, average or representative agents. The new, higher level entities have novel properties in relation to the properties the constituent parts have, i.e. whole departments do not act just like individual people, and ‘team-ness’ is not the same as ‘person-ness’. What is even more interesting is that these supposed abstractions can interact with the parts from which they emerged – a process known as *downward causation*. I won’t go into the problematic nature of the concept of emergence any further here – please refer to Richardson (2004) – suffice to say that the view that the process of emergence is captured by the expression ‘the whole is greater than the sum of its parts’ is far too simplistic.

In specially idealized complex systems such as in cellular automata (see the Wiki link below) the parts are very simple indeed, and yet they still display a great deal of emergent phenomena and dynamical diversity. Complex systems which contain more intricate parts are often referred to as *complex adaptive systems* or CASs, in which the parts themselves are described as complex systems. The parts of CASs contain local memories and have a series of detailed responses to the same, as well as different, contexts/scenarios. They often have the ability to learn from their mistakes and generate new responses (by combining with other parts for example) to familiar and novel contexts. Because of this localized decision-making/learning ability such parts are often referred to as (autonomous) agents. There is a profound relationship between simple complex systems (SCSs), i.e. complex systems comprised of simple parts, and CASs, i.e. complex systems comprised of intricate agents. The Game-of-Life, a particularly well-known SCS, shows how a CAS can be abstracted, or emerges, from a SCS! Intuition might tell us that a CAS is an intricate SCS with something 'extra' added, something different that drives adaptive evolution. The Game-of-Life demonstrates that our intuition is, as is often the case in complexity thinking, too simplistic. If you are unfamiliar with the Game-of-Life, 'invented' by John Conway, then I recommend starting with the Wiki at http://en.wikipedia.org/wiki/Conway's_Game_of_Life. The Game-of-Life, and other cellular automata-like systems, offer an entertaining way to learn a great deal about complex systems dynamics, and to begin to develop a deep appreciation for the systems view of the world.

COMPLEXITY AND INCOMPRESSIBILITY

Cilliers (2005) introduces the idea of incompressibility:

> We have seen that there is no accurate (or rather, perfect) representation of the system which is simpler than the system itself. In building representations of open systems, we are forced to leave things out, and since the effects of these omissions are nonlinear, we cannot predict their magnitude. (p. 13)[2]

It is this concept of incompressibility that leads us away from a managerial monism – a definitive theory of management – to a managerial pluralism (assuming organizations are complex rather than merely complicated) – in which many theories co-exist each with their own unique strengths and weaknesses. Restating Cilliers, the best representation of a complex system is the system itself, and any alternative representation of the system will be incomplete and, therefore, can lead to incomplete (or even just plain wrong) understanding. One must be careful in interpreting the importance of incompressibility. Just because a complex system is incompressible does not mean that there are not (incomplete) representations of the system that may be useful – incompressibility is not an excuse for not bothering. Indeed, dealing with complex systems may be precisely about finding descriptions and interpretive frameworks that are sufficiently simple to think about, but which are shown to be useful pragmatically. This is rather fortunate otherwise the only option available, once we accept the impossibility of an ultimate theory, is to have no theory at all – not a very satisfactory outcome (and contrary to what experience would tell us); I think I'd rather know something that is wrong rather than nothing at all. Knowing something and knowing how it is wrong is even better! Equally useful is knowing something that is wrong, *and* knowing why it is wrong.

Building on the work of Bilke and Sjunnesson (2002), Richardson (2005a) recently showed how Boolean networks (which are a type of SCS) could be reduced/compressed in such a way as to not change the qualitative character of the uncompressed system's phase space, i.e. the compressed system had the same functionality as the uncompressed system. If nothing was lost in the compression process, then Cilliers's claim of incompressibility would be incorrect. However, what was lost was a great deal of detail of how the different attractor basins (regions that describe qualitatively different system's behavior) are reached. Furthermore, the reduced systems are not as tolerant to external perturbations as their unreduced parents. This evidence would suggest that stable and accurate – although imperfect – representations of complex systems do indeed exist. However, in reducing/compressing/abstracting a complex system certain potentially significant details are lost. Different representations capture different aspects of the original system's behavior. We might say that, in the absence of a complete representation, the overall behavior of a system is *at least* the sum of the behaviors of all our simplified models of that system, although if there are 'contradictions' in the suggested behaviors, these should be treated with greater caution. Richardson (2005a) concludes that:

> Complex systems may well be incompressible in an absolute sense, but many of them are at least quasi-reducible in a variety of ways. This fact indicates that the many commentators suggesting that reductionist methods are in some way anti-complexity – some even go so far as to suggest that traditional scientific methods have no role in facilitating the understanding complexity – are overstating their position. Often linear methods are assessed in much the same way. The more modest middle ground is that though complex systems may indeed be incompressible, most, if not all, methods are capable of shedding some light on certain aspects of their behavior. It is not that the incompressibility of complex systems prevents understanding, and that all methods that do not capture complexity to a complete extent are useless, but that we need to develop an awareness of how our methods limit our potential understanding of such systems. (p. 380)

In short, all this is saying is that we can indeed have knowledge of complex organizations, but that this knowledge is approximate and provisional, meaning that it is less and less reliable the further we look into the future. This may seem like common sense, but it is surprising how much organizational knowledge is acted upon *as if* it were perfectly correct. Instead one should always consider that although this is what we think will probably happen, we should monitor everything carefully because it might not!

Of course, if simplified representations of a complex system can be useful then we have to admit that there could be many of them. The suggestion that there are multiple valid (meaning useful) representations of the same complex system is not new. The complementary law (e.g. Weinberg, 1975) from general systems theory suggests that any two different perspectives (or models) about a system will reveal truths regarding that system that are neither entirely independent nor entirely compatible. More recently, this has been stated as: a complex system is a system that has two or more non-overlapping descriptions (Cohen, 2002). I would go as far as to include 'potentially contradictory' suggesting that for complex systems (by which I really mean any part of reality I care to examine) *there exists an infinitude of useful, non-overlapping, potentially contradictory descriptions*. Maxwell (2000) in his analysis of a new conception of science asserts that:

> Any scientific theory, however well it has been verified empirically, will always have infinitely many rival theories that fit the available evidence just as well but that make different predictions, in an arbitrary way, for yet unobserved phenomena. (p. 18)

The result of these observations is that to have any chance of even beginning to understand complex systems we must be willing to approach them from many directions – we must take a pluralistic stance. This pluralist position provides a theoretical foundation for the many techniques that have been developed for group decision making, bottom-up problem solving, distributed management; any method that stresses the need for synthesizing a wide variety of perspectives in an effort to better understand the problem at hand, and how we might collectively act to solve it.

COMPLEXITY AND PLURALISM

The non-dogmatic attitude that complexity thinking imposes upon us undermines the whole notion of a unified theory of complexity, i.e. theoretical monism. A simplistic view of unification would be similar to the example above about computer languages. Unification of this sort would suggest that if we work very hard indeed, eventually we will not only have at hand all the relevant laws of complexity, but that these different laws could be derived from *one* underlying principle. This is very much the basis of Theories of Everything (TOEs) in the physical sciences. Although there will exist a plurality of theories, they will all be coherent in that they can be expressed in terms of a more fundamental/general language (likely to be a form of mathematics) without any loss of detail. We might refer to this as *commensurable pluralism*. However, if we assume that a complex systems perspective provides a more appropriate basis from which to understand our surroundings, then we must address the issue of incompressibility. Incompressibility leads to a different sort of pluralism altogether; a pluralism in which the different theories/representations are not all reducible to a fundamental language without loss of detail – even if we agree that a theory of individual psychology is more fundamental (i.e. lower-level) than a theory of team dynamics, *all* team dynamics will never be described in terms of individual psychology only. In such a pluralism the different representations are generally incommensurable with each other (i.e. not expressible in terms of each other), and rather than leading to a coherent TOE, a patchwork of overlapping theories results. Within such *incommensurable pluralism* there will be opportunities for limited translations, reductions and simplifications, but a TOE will never result. In this situation the critical importance of context also becomes apparent. Each approach in the patchwork will be valid only for a certain range of contexts, and so matching theory to context becomes ever so important. However, a feature of complex systems is that context recognition is not a trivial exercise, as to define a context we must ignore some aspects of the situation of interest (as in the process of abstraction described above). Contexts which appear similar may actually be quite different, and so the process of matching theory to context is problematic at best, which again highlights the importance of approaching real world problems from many different directions. Furthermore, complex systems evolve (in a qualitative sense) and so fundamentally novel contexts emerge requiring new theoretical syntheses. If we assume that human organizations are best described as complex systems then this has quite profound implications for management science; implications that are at odds with traditionalist views. It introduces a view of pragmatic learning, whereby different theories are formulated and used, and those that are most helpful are retained. This is an evolutionary view of the representation of complex evolving systems and takes us away from the idea of a hard, true real description of reality and towards one of multiple, changing understandings of what is going on. This is an evolutionary pluralism.

The main criticism traditionalists have of the 'others' is that by refusing to focus management studies on a single perspective/theory, the potential political and influential clout of management academics has been vastly reduced. According to Pfeffer (1993):

> Without a recommitment to a set of *fundamental* questions and without working through a set of rules to resolve theoretical disputes, the field of organization studies will remain ripe for a hostile takeover. (emphasis added, p. 558)

Donaldson (1995) built an entire book around this idea: *American Anti-Management*

Theories of Organization: A Critique of Paradigm Proliferation. Donaldson's book is an indictment of existing management science which, he claims, has fragmented into competing paradigms. Donaldson argues that this profusion of perspectives is driven not by a genuine need to further the body of knowledge, but by a 'push for novelty fuelled by individual career interests' typical of the academic environment.[3] He asserts that the resulting fragmentation of the field into mutually incompatible ideas has significantly weakened management science as an intellectual enterprise worthy of attention and support – I think this is confusing the marketing of theory with the process of theory development (the last thing we want to do is compromise the standards by which theory is developed for the sake of marketing).

Donaldson's book calls for building a unified theory of organizations. Clearly this is at odds with what has been discussed above. In my view, paradigm proliferation is healthy for management science – not a disease that needs to be eradicated – status quos are never maintained and are rarely healthy in the long term. Fragmentation is inevitable, but what we must learn to do better is work with this fragmentation rather than force a 'commensurable unification' upon it. Efforts to this end are readily apparent with the current trend for cross-disciplinary and multi-disciplinary research (which are themselves essential through the lens of complexity thinking). Such research will always be difficult by its very nature, and will not be overcome by pushing for a unifying framework, which will do no more than paper over the cracks (and in so doing severely limit our opportunities to develop richer understanding).

COMPLEXITY THINKING IN MANAGEMENT

In this section I will briefly outline three approaches for how complexity thinking might support organizational management. These different approaches are derived from three different schools of thinking within the complexity movement. These three schools are not isolated from each other, but themselves form a complex system of interrelationships. Despite their interdependence I still find it useful to divide the complexity movement into these divisions. The three schools/themes/divisions that I identify and discuss are: the neo-reductionists, the 'metaphorticians', and the critical pluralists.

THE NEO-REDUCTIONIST SCHOOL

The first theme is strongly associated with the quest for TOE in physics mentioned above, i.e. an acontextual explanation for the existence of everything. This community seeks to uncover the general principles of complex systems, likened to the fundamental field equations of physics.[4] The search for such over-arching laws and principles was/is one of the central aims of the general systems movement. Any such Theory of Complexity, however, will be of limited value. In Richardson (2005b) I suggest that even if such a theory existed it would not provide an explanation of every 'thing' in terms that we would find useful. If indeed such fundamental principles do exist they will likely be so abstract as to render them practically useless in the everyday world of human experience – a decision-maker would need several PhDs in pure mathematics just to make the simplest of decisions. I do not want to sound too critical here (I am an active contributor within this school of complexity) as we just need to consider how much valuable science has come out of the quest for a TOE. It clearly has been a highly motivating and productive idea. We just need to have realistic expectations for this way of doing science. It is quite likely that we would start to see diminishing returns if society (more specifically, funding councils) got too pre-occupied with this particular (reductionist) approach.

This complexity community makes considerable use of computer simulation in the form of bottom-up agent based modeling. The 'laws' such nonlinear studies yield provide a basis for a knowledge paradigm that is considerably broader than just bottom-up simulation, or any formal mathematical/computer-based approach for that matter.

The neo-reductionist school of complexity science is based on a seductive syllogism (Horgan, 1995 – perhaps meant semi-ironically):

> *Premise 1*: There are simple sets of mathematical rules that when followed by a computer give rise to extremely complicated patterns.
> *Premise 2*: The world also contains many extremely complicated patterns.
> *Conclusion*: Simple rules underlie many extremely complicated phenomena in the world, and with the help of powerful computers, scientists can root those rules out.

Though this syllogism was definitively refuted in a paper by Oreskes, et al. (1994), in which the authors warned that 'verification and validation of numerical models of natural systems is impossible', this position still dominates the neo-reductionist school of complexity in the (computational) social sciences. The recursive application of simple rules is certainly not the only source of complex behavior, and should not be seen as the only legitimate way to study complexity in human organizations (or anywhere else for that matter).

Despite all the rhetoric about reshaping our worldview, taking us out of the age of mechanistic (linear) science into a brave new (complex) world, many complexity theorists of this variety have actually inherited many of the assumptions of their more traditional scientific predecessors (they were very successful after all) by simply changing the focus from one sort of model to another, in very much the same way as some managers jump from one fad to another in the hope that the next one will be the ONE. There is no denying the power and interest surrounding the new models (e.g. agent-based simulation, genetic algorithms) proposed by the neo-reductionists, but it is still a focus on the model itself. Rather than using the linear models often associated with classical reductionism, a different sort of model – nonlinear models – have become the focus. Supposedly, 'bad' models have been replaced with 'good' models. This is a strategy we see in a wide variety of fields, not just the sciences. Although I myself do not have a great appreciation of the history of art, it does seem to me that new artistic ways of expression are more often thought of as 'different' rather than 'better' or 'worse'. I think this is a healthier attitude towards different methods.

THE METAPHORICAL SCHOOL

Within the organizational science community, complexity has not only been seen as a route to a possible theory of organization, but also as a powerful metaphorical tool (see, for example, Lissack, 1997, 1999; Richardson, et al., 2005). According to this school, the complexity perspective, with its associated language, provides a powerful lens through which to 'see' organizations. Concepts such as *connectivity*, *edge-of-chaos*, *far-from-equilibrium*, *dissipative structures*, *emergence*, *epistatic coupling*, *co-evolving landscapes*, etc., facilitate organizational academics and practitioners in 'seeing' the complexity inherent in socio-technical organizations. The underlying belief is that the social world is intrinsically different from the natural world. As such, the theories of complexity, which have been developed primarily through the examination of natural systems, are not directly applicable to social systems (at least not to the practical administration of such systems), though its language may trigger some relevant insights to the behavior of the social world which would facilitate some limited degree of control over the social world.

Using such a 'soft' approach to complexity to legitimate this metaphorical approach, other theories have been imported via the 'mechanism' metaphor into organization studies; a popular example being quantum mechanics (see McKelvey, 2001 for an example). While new lenses through which to view organizations can be very useful (see Morgan, 1986 for an excellent example of this), the complexity lens, and the 'anything goes' attitude that sometimes accompanies this perspective, has been abused somewhat. My concern is not with the use of metaphor *per se*, as I certainly accept that the role of metaphor in understanding is ubiquitous and essential. Indeed, in Richardson (2005b) it is argued that in an absolute sense all understanding can be nothing more (or less) than metaphorical in nature.[5] The concern is with its use in the absence of criticism – metaphors are being imported all over with very little attention being paid as to the legitimacy of such importation – the organization as an organism being a popular current example. This may be regarded as a playful activity in certain academic circles, but if such playfulness is to be usefully applied in serious business then some rather more concrete grounding is necessary. As van Ghyczy (2003) warns, 'Instead of being seduced by the similarities between business and another field, you need to look for places where the metaphor breaks down ... [M]etaphors are often improperly used' (pp. 87–88).

I refer to this school of complexity, which often uncritically imports ideas and perspectives via the mechanism of metaphor from a diverse range of disciplines, as the *metaphorical school*, and its adherents, *metaphorticians*. It is the school that perhaps represents the greatest source of creativity of the three schools classified here. But as we all know, creativity on its own is not sufficient for the design and implementation of successful managerial interventions. Recently, Evan Davis, reporting for the BBC (UK), blamed the current financial meltdown of the world's markets on creativity and innovation. He concluded that we should not ban innovation, but at least be wary of it (Davis, 2009).

THE CRITICAL PLURALIST SCHOOL

Neo-reductionism with its modernist tendencies can be seen as one extreme of the complexity spectrum, whereas *metaphorism* with its atheoretical, acritical, relativistic tendencies can be seen as the opposing extreme. In my view the complexity perspective (when employed to underpin a philosophical outlook) both supports and undermines these two extremes. What is needed is a middle path.

The two previous schools of complexity promise either a neat package of coherent knowledge that can apparently be easily transferred into any context, or an incoherent mish mash of unrelated ideas and philosophies – both of which have an important role to play in understanding and manipulating complex systems. In my opinion, not only do these extremes represent overly simplistic interpretations of the implications of complexity, they also contradict some of the basic observations already made within the neo-reductionist mold, i.e. there are seeds within the neo-reductionist view of complexity that if allowed to grow lead naturally to a broader view that encapsulates both the extremes already discussed as well as everything in between.

One of the first consequences that arise from the complexity assumption is that as we ourselves are less complex than the Universe (The Complex System), as well as many of the systems we'd like to control/affect, there is no way for us to possibly experience 'reality' in any complete sense (Cilliers, 1998: 4; see also the comments above regarding incompressibility). We are forced (by our very nature) to view 'reality' through (evolving) categorical frameworks that allow us to tentatively tiptoe our way through life with some vague direction in mind. The critical pluralist school of complexity focuses more on what we cannot explain, rather than what can be explained – it is a concern with limits, and how we take those limits into account when trying to understand the world around us. As such, it leads to a particular *attitude* towards models, rather than the privileging of one sort of model over all others.

And, rather than using complexity to justify an 'anything goes' relativism, it highlights the importance of critical reflection in grounding our models/representations/perspectives in an evolving reality. The keywords of this school might be *pluralism*, *criticism*, *open-mindedness* and *humility*. Any perspective whatsoever has the potential to shed light on complexity (even if it turns out to be wrong, otherwise how would one know that it was wrong?), but at the same time, not every perspective is equally useful/applicable in any given context (try fixing your car with prayer rather than with a good mechanic). Complexity 'thinking' is the art of maintaining the tension between pretending we know something, and knowing we know nothing for sure; it is a state of mind rather than a particular perspective.

THE THREE SCHOOLS AND MANAGEMENT

Now that we have identified and discussed the three schools of complexity, how does each one contribute to the management of human organizations?

The first one, neo-reductionism, is the easiest as it simply adds a new collection of analytical tools to the decision-makers tool set. These tools will probably impact the fields of management science and operations research the most, providing some very powerful tools to facilitate the decision-making process surrounding larger strategic questions. Indeed such models are ideal for exploring that class of question where individual behavior matters only as a contribution to group behavior. They will probably not contribute to rather more mundane day-to-day management activities – it is unlikely that the development of an agent-based model will help much in deciding if to promote someone or not, or whether to change the supplier for the hallway coffee machine (techniques such as causal mapping and multi-criteria decision analysis are 'complexity' tools better matched to such 'micro' questions). There are certain types of problems that can benefit from nonlinear analytical models and some problems that will not. This school of complexity seems to be the most visible at present, and is probably the easiest of the three to (attempt to) apply. Given the immense computational resources needed to utilize the neo-reductionist's tools, there is also a certain level of glamour and excitement associated with this sort of complexity application; this seems to have captured the imagination of the management world, even though the problems it can usefully be brought to bear on are limited.

The metaphorical school of complexity can certainly play a part in the day-to-day activities of management. Given that our personal worldviews determine to a large extent what we 'see' and how we 'manage' what we 'see', replacing/enhancing that worldview with a perspective that is rather more sensitive to the complexities that are inherent in daily experience, can have a profound effect. Richardson et al. (2005), for example, considers project management through the lens of complexity-inspired metaphors. It is difficult to fully appreciate the influence the widespread usage of complexity-inspired metaphors will have, but I would like to think that many of the shortcomings of the dominant command and control metaphor (which, unfortunately, has become rather more than a metaphor) will be mitigated. Of course, replacing one worldview with another may create as many new problems as it solves. It'll be interesting to see what these new problems will be. (Although, seeing management as a problem solving process is itself a feature of the command and control attitude.)

The metaphorical school does not only legitimate the use of complexity-inspired metaphors though; it is often used to justify a fully blown pluralism in which anything goes. We have to be careful that our wish to explore all possibilities does not lead to chaos (and I don't mean this in the mathematical sense). Quoting van Ghyczy (2003) again, 'It's tempting to draw business lessons from other disciplines – warfare, biology, music. But most managers do it badly' (p. 87). I would also add that many academics also do this badly, but this is perhaps due to the human weakness for seeking lessons from wherever that happens to support our current strand of thought.

The critical pluralist school of complexity also has implications for all aspects of management, although it is possibly one of the hardest to 'teach'. It encourages not only management, but all participant members of an organization, to approach everything they do in a critical way and to maintain some (ontological) distance from their ideas, i.e. to not take our ideas of organization too seriously – use our ideas to guide, or initiate, our thinking about organizations, not to determine our thinking. Complexity 'thinking' is a particular attitude towards our ideas of the world and the world itself, not a particular tool/method, or even a particular language. The last school is rather more philosophical than the first two and is also the hardest to describe in any complete sense but we need to try.

COMPLEXITY AND PHILOSOPHY

Managers seem reluctant to study philosophy. They're not alone. This is not particularly surprising given that many books on the subject are often devoid of any practical recommendations. However, when I talk about a philosophical attitude I'm not saying that we all need to go out and invest considerable time in penetrating obscure texts. Philosophy is a study of what underlies choice, and in both management and research, choices abound. Researchers have to choose which methodology they are to employ in understanding a particular aspect (which of course also has to be chosen) of management; the boundaries of the research study need to be chosen (which is strongly dependent upon research methodology), etc. Managers have to continually decide which information is required to make a particular decision; how to interpret that information for the purposes at hand, and even choose what the actual purpose might be, as well as what the issue is that needs to be decided upon (although, often this is done very much unconsciously without much attention to the actual framework within which they have been 'taught' to operate).

From the perspective of the researcher Hughes (1990) suggests that philosophy underpins the whole selection process because:

> ... every research tool or procedure is inextricably embedded in commitments to particular versions of the world and to knowing the world. To use an attitude scale, to take the role of a participant observer, to select a random sample, to measure rate of population growth, and so on, is to be involved in conceptions of the world which allow these instruments to be used for the purposes conceived. No technique or method of investigation (and this is true of the natural sciences as it is of the social) is self-validating: its effectiveness, that is its very status as a research instrument making the world tractable to investigation is, from a philosophical point of view, ultimately dependent on epistemological justifications. Whether they may be treated as such or not, research instruments and methods cannot be divorced from theory; as research tools they operate only within a given set of assumptions about the nature of society, the nature of human beings, the relationship between the two and how they may be known. (p. 11)

When managers choose to adopt a particular perspective, or set of procedures, or what issue to focus upon, these choices are philosophically equivalent to the researcher's selection of a particular methodology. Both sets of choices are underpinned by particular views of how the world we observe is constructed, and how it should respond to our actions upon it. More often than not we are unaware of the commitments that our choices imply. It is not a question most of us have been taught to ask. It is not a question we have evolved to be too concerned with either. Of course, science claims that it does, but often established theories and dominant schools of thought and journals mean that even researchers do not think enough about this. Managers, as well as most of us at large, are very rarely concerned with the underlying assumptions upon which our choices are made. If we were, we would be rather surprised as to the absurdity of some of our most cherished beliefs.

Philosophers often refer to the dominant worldview (or philosophy) of the average layperson as *naïve realism*. The 'naïve' part is possibly a poorly chosen label as it would seem to indicate that all of us who are not philosophers are a little daft, in that we have been so poorly misguided into ever believing that realism could possibly be a sensible way to view our surroundings. I think, given that much of our sensory and decision making equipment has evolved in a way that naturally leads to a kind of realism, perhaps we can be forgiven for not knowing any better. Maybe common sense realism is a more positive way of distinguishing a layperson's realism from a philosopher's realism. Evolution only requires that something be 'good enough' and not that it be perfect, and so a layperson's views reflect the wonderful openness of pragmatism.

Realism is based on a what-you-see-is-what-you-get (or WYSIWYG for those fluent in computer jargon) worldview, i.e. that our senses tell us accurately what the world is comprised of and how those parts interact – what-you-sense-is-what-there-is (WYSIWTI), if you like. The first implication of realism is that the way in which we 'see' the world is quite independent of what our senses, and our beliefs, guide us to 'see'. This is quite contrary to the quote given above which suggests that our senses and beliefs profoundly affect what we 'see'. If our senses are truly unbiased (as naïve realism suggests) then understanding the world around us simply becomes a process of map making. For this reason realism is often also referred to as *representationalism*.

A second implication of realism is to regard causality as a first order process, i.e. if a change in object A results in a change in object B we have a tendency to assume that such a correlation points to a causal mechanism – 'A caused B to ...'. So not only do the objects A and B exist as such, they also affect each other directly. The 'existence' of A and B would seem to be a trivial matter especially when considering objects such as cars and computers, but what about concepts like 'consumer confidence' or 'social capital'? Furthermore, given WYSIWTI, the possibility that it is an unseen object C that affected A and B (or mediated the affect), or that two unrelated objects C and D affected A and B directly, or that the change in B resulting from a change in A was no more than a coincidence (and therefore not causal even if there was some correlation) are all scenarios that are omitted from a simplistically realist perspective. The natural sciences have developed tools to allow us to 'see' objects that remain 'unseen' with the naked eye, but even here any explanations offered must necessarily be based on what has been detected.

Quite often realism is associated with 'linearity', but this would be a mistake. The advent of the computer has allowed us to 'model' scenarios in which complicated loops of interaction can be represented and explored, a trick which the human mind seems woefully inept at doing. The main consequence of realism that concerns me here is that it leads to an overconfidence in what we have represented and analyzed as being exactly how the real world works. Quite clearly this is not a view devoid of merit. If it was then our capacity to successfully achieve anything would be very much lower than it actually is. Clearly, to a useful degree, realism produces some rather good results.

Given the successes of modern science, it is not surprising that realist viewpoints dominate Western thought – it is a natural way to view things, and such impressive machines as computers have been built that surely prove the power of realist thinking. Relating this back to philosophy, the success of modern science is arguably the reason that philosophy has fallen by the wayside. If science leads to correct knowledge all the time, then what is the point of questioning its underlying assumptions; surely the way in which modern science and the realists view the world is how the world *is*? Each new management fad promises to provide the ultimate answers to the hard questions troubling practicing managers, which again encourages philosophical ignorance. Why bother thinking too hard if there is a framework 'out there' claiming to do the thinking for us?

Two of the big questions for philosophers are what objects *exist* and how can we *know* about those objects. Jargon-wise, the study of what exists is referred to as *ontology* and the study of how we come to know these objects of existence (the study of knowledge) is referred to as *epistemology*. These two areas of interest have been enthusiastically investigated for at least 2,500 years, until very recently that is. The Newtonian view of the Universe leads to an 'exquisitely intricate timepiece' model, i.e. the Universe is a really big machine. As a big machine it can be taken apart, its parts can be studied in isolation, and knowledge of the whole can be accurately gleaned by summing together the knowledge of its component parts. In popularized views of modern science, there is something referred to as the scientific method which guides us in the study of these parts. So ontologically the Universe is a big machine, and epistemologically we have the scientific method to give us knowledge of the Universe's parts and eventually the Universe as a whole.

What is often missed from popular views of modern science is that science does not always work very well, and that there is no such well-defined process called the scientific method. This may come as a surprise to the many opponents and critics of modern science, but most decent scientists are well aware of their chosen occupation's shortcomings. Questions of ontology and epistemology really haven't been answered to complete satisfaction, thus there is still very much a role for philosophy.

The famous physicist Louis de Broglie once said 'May it not be universally true that the concepts produced by the human mind, when formulated in a slightly vague form, are roughly valid for reality, but that, when extreme precision is aimed at, they become ideal forms whose real content tends to vanish away?' (quoted in Cory, 1942: 268). This suggests that we should use scientific understanding (not knowledge) to guide our decisions, not determine them as such understanding is only correct in a 'vague' sense. This is true of all understanding once we accept the limitations of the realist worldview. Rather than regarding our knowledge as faithful maps of reality we must see it as a potentially useful, but not necessarily so, caricature of reality, or as a metaphor. This follows from the fluid and complex nature of systemic boundaries as seen from the complexity perspective. Causality is complex, intricate, multi-ordered, and intractable (in an absolute sense). All this suggests a renewed concern with ontology and epistemology and therefore with philosophy. What is ironic is that, though it has taken a revolution in science (spurred by a technological revolution which resulted from the dogmatic application of realist thinking for the past 400+ years) to bring complexity to the fore, philosophers have been concerned with complexity for hundreds if not thousands of years. So if you do find the time, and are willing to put in the hard work often necessary to understand many philosophical writings, you may well be surprised with the nuggets of wisdom you will uncover in even the oldest texts. Fortunately we are blessed with 'Dummies Guides' to get us started!

SOME CONCLUSIONS

The aim of this article was to consider the various ways in which complexity might inform managerial action in a general sense. There are various tools derived from complexity science that might be used in the analysis of certain managerial problems. However, it is the implications of complexity thinking for the 'managerial attitude' that I have focused on here as I believe the shift from a linear simplistic attitude to a nonlinear complex attitude is significantly more challenging than a simple switch from one framework/tool to another as is more common in our faddish modern world.

The concept of incompressibility discussed above would suggest that attempting to capture the complex systems-derived implications for organizational management in some short snappy conclusions would at best be a limiting exercise, and at worst rather irresponsible (even unethical!). However, in the hope that you have read the preceding pages and not just jumped to the conclusions, I will attempt to do just that with the knowledge that you will appreciate that this is a problematic exercise to say the least. The laws of complex organizational management, therefore, might be listed as follows:

1 ***Just because it looks like a nail doesn't mean you need a hammer:*** A complex systems view acknowledges that context recognition is problematic, and as such deciding what to do is not a simple exercise of repeating what you did the last time you were in the same situation. The chances are the situation is quite different.
2 ***Decisions made by the many are often better than those made by a few:*** A precursor to any decision has to be a thorough consideration (critique) from multiple perspectives (pluralism). This might be the application of a variety of different models, or simply just asking more than one person for their opinion. Such an approach quite naturally leads to creative thinking, and enables the development of a richer understanding concerning a context of interest before a decision is made. Beware, however, as 'too many cooks may spoil the broth', and in situations where time is not readily available, the leadership of an individual may prove more effective than attempts at group decision making.
3 ***Expect to be wrong (or at least not completely right):*** There are limits to how pluralistic and critical our decision making processes can be. But even with all the time and resources in the world (and a commitment to do the 'right' thing), decisions can only be made based on our best current understanding, and that understanding will always be incomplete. Everything is connected to everything else. We can't consider everything so we infer somewhat artificial boundaries to help us make a decision – without those boundaries we are helpless, with them our responses are limited (but at least we have some responses!).
4 ***Flip-flopping is OK:*** Contrary to the beliefs of certain US politicians, being prepared and confident enough to change one's mind when it becomes clear that one's model is proving ineffective (and even counterproductive) is actually a virtue, not a sin. The complex organization evolves in unforeseeable ways, and as such we must be prepared to 'move with the times'. The simple act of making a decision (based on past experience) can change how the future unfolds. Don't make the mistake of escalating one's commitment in the face of mounting contrary evidence. Dogmatism is rarely an effective long term strategy.

These bullets may be common sense to the experienced manager (endowed with an innate understanding of human networks). I certainly hope so! What is particularly interesting about complexity science is that it provides a scientific way of making these points. Good science has a tendency to change what common sense is over time, and I am excited at the prospect of an emerging systemic common sense. The complex systems view really is a profoundly different way of understanding the world from what we in the West (primarily) have become accustomed to. It is significant that these ideas of pluralism and of complexity science being an art find strong echoes in many of the chapters of this Handbook.

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NOTES

1 'Nonlinearly' simply means that the parts are constructed in a way such that the output from one particular part is not necessarily proportionate to its input. The weather system is an oft cited example in which small additions of energy don't necessarily lead to small changes in the system's behavior.

2 This statement risks conflating the concept of incompressibility with the problem of identifying a bounded description of a complex system. These two concerns are not equivalent; just because a particular system cannot be bounded easily is not what incompressibility is all about. Incompressibility derives from the interacting nonlinear feedback loops that exist even in well bounded complex systems, i.e. a bounded complex system is still incompressible.

3 Donaldson's argument may account for why certain perspectives are more dominant than others, it does not explain why there is a 'profusion of perspectives' in the first place. I would tend to think that if there was even a whiff of an ultimate theory of management then I doubt that the 'individual career interests' of academics could prevent its development. Maybe the fact that after all the effort that has gone into trying to find this elusive organizational theory of everything (OTOE) we still only have a 'profusion' suggests that a 'profusion' is the optimal situation, and that an OTOE does not in fact exist (or that it is at least way beyond the grasp of mere mortals).

4 It is likely that these two research thrusts, if successful, will eventually converge if it is assumed that some kind of complex systems representation of the Universe as a whole is valid.

5 Metaphor is the description of certain aspects of one thing in terms of certain aspects of another. If we consider the Universe to be one 'thing' then human knowledge is the partial representation of the Universe in terms of the 'things' that constitute human language. Language itself determines to a great extent what aspects of reality are promoted to the 'foreground' – i.e. what we pay attention to – and what aspects are demoted to the 'background' – i.e. what we ignore – in the same way that the fox metaphor – 'He is as cunning as a fox' – highlights a particular trait of an individual and compares it to the cunningness of the fox. At the same time traits like the fox's shyness, for example, are ignored. By describing knowledge as a metaphor, its biased and limited nature are highlighted.

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B

Complexity and Managing

22

Implications of Complexity Science for the Study of Leadership

Russ Marion and Mary Uhl-Bien

INTRODUCTION

A number of leadership scholars and popular writers have recently focused attention on organizational issues that cannot be effectively solved with traditional top-down (centralized) leadership approaches (Marion and Uhl-Bien, 2001; Schneider and Somers, 2006; Hazy et al., 2007; Plowman and Duchon, 2008). Heifetz (1994) and Uhl-Bien, Marion, and McKelvey (2007) have called these sort of problems, adaptive challenges; Snowden and Boone (2007), with minor liberties, would define these issues as 'Cynefin, pronounced ku-nev-in, … a Welsh word that signifies the multiple factors in our environment and our experience that influences us in ways we can never understand' (p. 70). They are problems that are characterized by changing, interactive complexities of a degree that defy direct or existing solutions. Scholars seeking to understand adaptive behaviour and how leadership can best integrate with it are increasingly turning to complexity theory, or the science of complexly interacting and changing events, to better understand leadership and adaptive challenges in organizations (Stacey, 2001; Plowman et al., 2007a; Hazy and Silberstang, 2009; Hunt et al., 2009; Lichtenstein and Plowman, 2009; Uhl-Bien and Marion, 2009).

Adaptive issues can be categorized as environmental problems that are too complex to be easily resolved or that require social engagement and support (Heifetz, 1994; Uhl-Bien et al., 2007). The infamous travelling salesman problem exemplifies the first: A travelling salesman wants to visit all the cities in his or her territory without going through the same city twice. The problem is virtually impossible for an individual to think through, but several simulations based on complexity logic have produced reasonably good answers (Michalewicz, 1999). More practical examples involve the generation of innovation within R&D operations (Osborn and Marion, 2009), stock market decline (Martin and Eisenhardt, 2004), and supply chain efficiency and effectiveness (Bonabeau and Meyer, 2001). Examples of the latter categorization include public debate over social issues such as pollution by production firms (Heifetz, 1994).

Solutions that are being proposed for dealing with adaptive problems are broadly covered by Ross Ashby's (1960) famous dictum: It takes complexity to defeat complexity. Complex problems are best tackled by complex responses. Complexity theories of leadership explore strategies leaders can use for advancing and enabling such complex response.

This chapter describes emerging complexity perspectives of leadership and explores the differences among these perspectives. These different perspectives all ask, 'What is the role of leadership in complex organizational systems?' They investigate the nature and outcomes of adaptive systems, leadership as a collective dynamic, and how leaders generate and foster complexity dynamics in the organization. But they answer these questions in different ways. We describe these perspectives and then identify trends in the field. We also address questions yet to be explored. Finally, we develop challenges that the field of complexity leadership will need to overcome as it moves forward.

DEFINITIONS, QUESTIONS AND ASSUMPTIONS

Complexity theory is defined by Coveney (2003) as the 'study of the behaviour of large collections of … simple, interacting units, endowed with the potential to evolve with time'(p. 1058). Prigogine (1997) extends Coveney's insight by defining complexity as interactions among many dynamic degrees of freedom, the outcome of which cannot be predicted. Colandar (2000) adds that complexity is the study of how many interacting units can produce relatively simple behavioural patterns. Applied to organizations, organizational complexity is a science of survival and productivity in very complex, turbulent environments and complexity leadership is the application of complexity science to the study of leadership in organizations and their environments.

Complexity leadership theorists have noted the potential for complex dynamics to enhance the responsiveness of organizations to complex environments (often referring to the globalized, highly diversified and competitive knowledge economy; Uhl-Bien et al., 2007), and are consequently exploring that potential for the workplace and its implications for leadership. Complexity perspectives of leadership ask, what is leadership in complex systems? This is more than a definitional solicitation; this question, 'what is leadership', is a challenge to re-conceptualize the very nature of leadership by breaking away from traditional premises and assumptions and seeking leadership characteristics that have been overlooked in the past. For example, leadership is almost universally associated with hierarchical influence and top-down control (Jermier, 1998). Complexity leadership theory asks if there are alternative ways to understand how change and influence, hence leadership, occur.

There are a number of defining characteristics of complexity leadership and several of these will be described in this chapter, but one that is particularly pertinent is the notion that change (e.g. creativity, adaptation, learning) emerges from a collectivist dynamic. Collectivism, as opposed to methodological individualism, has been hotly debated behind the scenes of leadership scholarship and has even found its way into the literature (Friedrich et al., 2009). But whereas Friedrich et al. (2009) define collective leadership as multiple intelligences acting individually (methodological individualism), complexity theory would define it as a collective behaviour that accrues when (1) ideas emerge from interactions among individuals and groups (Lichtenstein et al., 2006), and (2) multiple ideas interact in multiple venues, combining, elaborating, and diverging in ways that obscure their original manifestations and can only be described as collective ideas.

THEORIES OF COMPLEXITY LEADERSHIP

In general, there is relatively uniform agreement among theorists studying complex leadership on the basics of complexity theory, such as interactive network dynamics, emergence, unpredictability, uncertainty, and pressure. Some perspectives of complexity leadership do differ somewhat because of the underlying science with which they associate (complexity evolved largely from observations in biology and physics). They differ in the aspects of complexity theory the authors choose to emphasize (Lichtenstein and Plowman, 2009, for example, emphasize emergence while Hunt and colleagues emphasize the role of administrators in setting up organizational structures and systems). Another significant difference lies in the assumptions of the various approaches about the management role in complex dynamics, particularly as it relates to control of complex dynamics. This section is structured around these three themes: the underlying science behind complexity leadership, the basic emphases of the different perspectives, and the role of management and control in complexity leadership.

Underlying science

Complexity theory generally evolved out of biology and physics (with a nod to economics), and both have shaped the way we perceive complexity theory and complexity leadership. Researchers in complexity tend to blend the two traditions in their writing, yet physics and biology say different things about change in complex dynamics.

Physicists, inspired by Ilya Prigogine (1997), describe complexity as the build-up of pressures – attributable largely to external pressures – until the system reaches a far-from-equilibrium state in which the system precipitously releases the pressure and new order emerges (i.e. phase transition). This starkly contrasts with traditional theories, which largely describe organizations as equilibrium-seeking systems (Negandhi and Reimann, 1972). The physics-based perspective is extensively used in the organization theory complexity literature to describe dramatic change events (cf. McKelvey, 2003). Indeed, it probably is the dominant explanation of dramatic change in that literature. However, few of the leadership complexity perspectives described in this chapter can be said to fall exclusively within this school, although Goldstein et al. (2010) described this phenomenon in some detail in Chapter 4 of their book, and Plowman and Duchon (2008) describe far-from-equilibrium as one premise of their research.

Biologists envision a complex, networked evolutionary dance among numerous species in which patterns of interaction, called niche, emerge. Kauffman (1995) argues that this process is motivated by pressures from the patterns of interaction in the network, referring particularly to conflicting constraints (Kauffman, 1995). But while pressure helps the system elaborate and change, it need not build up to create change, as advocated by physicists. Brian Arthur (1989), for example, described the emergence of new technologies with language that focused on the role of interactive dynamic itself, without referencing the accumulation of pressures; Kauffman described change as a fitness search by interactive species; and Marion (1999) described the emergence of microcomputers using Kauffman's arguments about *NK* systems (For more details on Kauffman's *NK* and *NKCS* models, see Vidgen and Bull, this volume).

The complexity leadership perspectives that most reflect the heritage of biology are those that focus on the creative potential of interactive dynamics themselves. Uhl-Bien et al. (2007), for example, define their concept of adaptive leadership relative to networked interactions under conditions of such things as interdependency, interaction, heterogeneity, and task related conflicts. These dynamics foster creative ideas that, in turn, interact within the complex network, combining, diverging, elaborating, and forming even higher-level ideas. Both Schreiber and Carley (2006), and Osborn, et al. (2002) likewise focus on the convergent and divergent outcomes of interaction. Schneider and Somers (2006) add the biology-based notion of leadership as tags, or functions that catalyze certain complex behaviours in a system. In the biological perspective, change is constantly occurring and will occasionally be dramatic (i.e. species extinction and re-speciation); pressure certainly plays a role in elaboration but does not necessarily play a role in the intensity of change (i.e. major change can result from small perturbations, etc.).

Much of the literature discusses the nature of interactions among individuals, groups, and artefacts, and to this extent they are drawing on the heritage of biology. However, that literature also tends to talk about dramatic change relative to far-from-equilibrium and the release of pressures, thus drawing on the physics heritage. The theoretical lenses by which complex organization and leadership is understood is institutionalized in the process in favour of the physics perspective, and, we could loose track of the significant understanding (ie. the change perspective of biolgists) in scholarship and research as a consequence.

Major orientations

The literature on complexity leadership exhibits different orientations that underscore something of the scope of this body of work and also reveals differences in authors' treatments about the function of complexity leadership. Guastello's (2007) research agenda, for example, is focused on understanding how catastrophe theory – a relative of complexity theory – explains social behaviour and the emergence of informal leaders. Catastrophe theorists such as Guastello propose that complex systems 'wander' around in social space until they reach and move across a cusp, thus leading to new structures; it is another way to understand emergent phenomena in complexity studies. Lichtenstein and Plowman (2009) focus on leadership and emergence; this theme is also evident in the 2010 book that Lichtenstein wrote with Goldstein et al. Schreiber and Carley's research is defined by their methodology, dynamic network analysis, which explores the nature and outcomes of interactions in a networked environment and how informal leadership emerges from, and enables effectiveness within, this context. Solow and his colleagues have demonstrated how the introduction or removal of actors from a small complex group can alter the system in sometimes surprising ways (Solow et al., 2002), as when a person is removed who is seemingly unproductive but actually catalyses productive actions in others. Writing with Szmerekovsky (2006), he similarly examined the effects of managerial control on small group dynamics.

Surie and Hazy (2006) identify an emphasis they call generative leadership; this emphasis is further elaborated in Goldstein et al. (2010). In Surie and Hazy (2006), generative leadership is conceptualized as a managerial role, an individual who acts deliberately to shape the complex dynamic. Goldstein et al. (2010) appear to broaden the definition of generative leadership to a more bottom up, interactive process.

Uhl-Bien et al. (2007) describe complexity leadership relative to three functions: adaptive, administrative, and enabling leadership. Adaptive leadership refers to informal, interactive actions that influence local behaviours, and which interact with complexity dynamics to generate adaptive and innovative outcomes (e.g. the emergence of creativity, learning, and adaptability) for the firm. Administrative leadership refers to managerial leadership that occurs in the formal systems and structures of the organization and are designed to generate business results through efficiency and control. Enabling leadership operates in the interface between the other two. It helps fosters conditions necessary for adaptive leadership to emerge and helps loosen up administrative structures to allow adaptive outcomes to be incorporated into administrative systems to generate productive business results.

Osborn et al. (2002) explore the contexts within which leadership occurs and are quite interested in what they see as the inevitable role of authority in organizations. They describe four leadership contexts – stability, crisis, dynamic equilibrium, and edge of chaos – only the last of which is appropriate for complexity leadership. More recently, Snowden and Boone (2007) echoed this emphasis. (Interestingly, both the Osborn et al. paper and the Snowden and Boone article won best paper of the year awards in their respective journals.)

Ralph Stacey (2001) offers a perspective called complex responsive systems, which refers to complex inter-adjusting interactions among individuals from which patterns of communication behaviour and consciousness emerge (Griffin, 2001; Stacey, 2001). The role of leadership is to sustain the identity and purpose of the dynamic system. Leaders understand the implications of individual actions better than others and are consequently respected and followed because of that capability (Griffin, 2001). This perspective of leadership diverges from the others in that it focuses on explaining, rather than influencing, how patterns of behaviour emerge in organizations and society.

The role of management

Finally, complexity leadership theorists differ in their orientation to control, or management. Surie and Hazy (2006) propose that complexity leaders are agents who manipulate organization designs and deliberately tune the system. Similarly Goldstein et al. (2010) criticize 'an unfortunate belief that emergence was somehow a spontaneous process that was somehow self-generated, outside the reach of managers and executives.' While Goldstein et al. are not always clear as to whether generative leadership is a complex group dynamic or a role of managers, they seem to lean toward the latter in proposing that generative leadership produces a 'clear-minded assessment about the actual flow of energy and resources' (p. 179), 'actively engenders a culture of engagement and respect' (p. 180) and, stabilizes 'emergence by developing new and effective routines, and … [creates] partnerships and coalitions that increase the legitimacy of the emergent entity' (p. 186).

In contrast, Uhl-Bien et al. (2007) argue throughout their body of work that complex dynamics are too complex to be managed or designed. They propose that leaders *enable,* rather than design, complex contexts in which creativity, adaptability, and learning is maximized. Enabling leaders are controlling only to the degree that they build structures for inhibiting or redirecting ideas that are inconsistent with organizational missions or damaging to organizational functions. Uhl-Bien and her colleagues relegate the control function more to administrative leadership, arguing that it is entangled with enabling and adaptive leadership in ways that maximize creative outcomes.

Uhl-Bien et al. do argue, along with Griffin (2001), Plowman and Duchon (2008), Schreiber and Carley (2008), and Goldstein et al. (2010) that complexity involves dynamic networks of influence. While some individuals and groups have more influence than others, their interactions are inter-adjusting; that is, individuals and groups tend to shape themselves around the preferences of others. Control is different, however; it occurs when the preferences of one person or group preempt those of another. At the core of complexity leadership approaches is the belief that influence is effective in the production of creativity and is preferred over control.

ISSUES IN COMPLEXITY LEADERSHIP

There are several basic questions that are typically asked in complexity leadership studies; we will focus on four such questions as we further develop complexity premises. The first is, why is it important to understand leadership and organizations as complex dynamics? Second, how do leaders foster complex dynamics, assuming such dynamics are beneficial? Third, the antithesis of complexity is bureaucracy, with its hierarchical structuring, functional differentiation, and careful control procedures; so how do complexity and bureaucracy coexist? Finally, does complexity point to alternative ways to perceive leadership? We will answer each of these questions in turn, and will then examine trends in complexity leadership theory – questions that are now being explored or that need to be explored.

The first question, why understand leadership and organizations as complex dynamics, is quite reasonable and important. Most studies of leadership still assume that 'A certain amount of predictability and order exists in the world' (Snowden and Boone, 2007: 70). They still tend to ascribe to the notion that leadership brings human dynamics into alignment with organizational goals (Barnard, 1938), to assume independence among cases, and to be person-centred and top down. Why, then, should we change?

We can answer this in several ways. First, just as physicists and neoclassical economists have long finessed 'troublesome' nonlinearity, or chaos, in their observations and equations, only to find recently how crucial nonlinearity is to understanding physical and economic phenomena (Gleick, 1987; Ormerod, 1998, 2000), organizational theorists have similarly ignored or attempted to finesse complexity in their observations (e.g. by attempting to control informal group dynamics). Complexity can be a resource that helps organizations respond to turbulent environments and which is conducive to creativity, learning, and adaptability (Stacey, 2001; Tsoukas and Chia, 2002); thus complexity theorists are attempting to understand how to work with this dynamic. Second, social scientists are beginning to understand that it takes complexity to defeat complexity, paraphrasing Ashby's (1960) famous observation. Or to re-phrase in the terminology of Heifetz (1994): It takes adaptive leadership to address adaptive problems. Terrorism will not be defeated by a predictable response (Marion and Uhl-Bien, 2003); bacterial infections will not be abolished from this planet by stable antibiotics; and hyper-turbulent organizational environments will not be defeated by a stable commodity economy.

This leads to a third, closely related argument for complexity leadership: The modern economic environment is highly complex. It is beset by globalism, rapidly changing technologies, and a focus on knowledge rather than stable commodities (Boisot, 1998; Drucker et al., 1998; Hitt, 1998; Hamel, 2009). To respond to this economy, organizations must be characterized by emergent creativity, they must be able to learn quickly, and they must be able to adapt rapidly to changing conditions; that is, they must be complex.

The second common question in the complexity leadership literature is, how do leaders foster complex dynamics? It is important to note that the word, foster, was carefully chosen. Many theorists suggest that leaders do not create complexity for it is too complex to be created (Kauffman, 1993, 1995); rather, they enable the conditions in which complexity can emerge (see discussion alternatives arguments above).

Uhl-Bien et al. (2007) and Uhl-Bien and Marion (2009) identify several such enabling conditions. They argue that people and ideas should be enabled to interact, and they point to the interactive environment at IDEO Product Development to illustrate (Thomke and Nimgade, 2007). Agents and ideas should be interdependent in order to foster conflicting constraints (Kauffman, 1995). Enabling leaders should promote heterogeneous skills, worldviews, preferences, and ethnicities in order to inject multiple information sets into problem-solving dynamics. Enabling leaders should create adaptive tension (tension that is not focused on specific goals), thus fostering creativity and supplementing the tension of conflicting constraints (McKelvey, 2008). Lichtenstein and Plowman (2009) add that enabling leaders foster complexity with actions that include the following:

> Disrupt existing patterns through embracing uncertainty and creating controversy, encourage novelty by allowing experiments and supporting collective action, provide sensemaking and sensegiving through the artful use of language and symbols, and stabilize the system by integrating local constraints (p. 617; see also Plowman et al., 2007b).

Third, how does complexity coexist with bureaucracy? Bureaucracy is inevitable and pervasive; the prediction by some post-bureaucratic theorists of bureaucracy's demise (Heckscher and Donnellon, 1994; Grey and Garsten, 2001; Maravelias, 2003) is unlikely for most contemporary organizations (for exceptions see Brafman and Beckstrom, 2006). Bureaucracy and complexity coexist effectively when those in positions of authority acknowledge the existence and importance of complexity dynamics, and supplement their roles with enabling behaviours. At IDEO Product Development, managers enable interaction by providing appropriate spaces for people who work together (Thomke and Nimgade, 2007). To enable discussions at Sun MicroSystems' iWork, the managers have designed workspaces for its hardware design group that resembles a country club lounge (Cross, 2007). In each case, bureaucratic personnel have understood the importance of complex dynamics, and have taken steps to enable their processes.

Interestingly, although this needs further research, it appears that complex dynamics may actually be enabled and enhanced by the interaction of bureaucracy and standard organizational behaviour (the regular behaviour of groups as they perform their responsibilities). Physicists identify a dynamic called dampening, and illustrate by positioning a beaker of water such that a ball oscillating regularly on a spring dips into the water at the end of each cycle – for organization purposes, translate ball as informal work dynamics and water as bureaucracy. The interaction between the pendulum-like motion of the ball and the restricting force of the dampening agent (the water) can cause the ball to move chaotically (Baker and Gollub, 1990). We propose similarly, but from a complexity and organizational perspective, that when regular work behaviour interacts with a restricting force such as bureaucracy, the social dynamic may move towards a more complex state than existed before. Evidence of this process in social behaviour is scant at present, but intriguing. Hazy (2003, 2008) observed this apparent phenomenon in a computer simulation in which generative leadership (Surie and Hazy, 2006) conflicted with leadership of convergence; the result was tension that fostered the uncertain behaviours of complexity. Marion, Uhl-Bien, and their colleagues have observed similar phenomena in several as yet unpublished grounded research studies in large organizations (e.g. Marion et al., 2009). Interestingly, McKinley and Scherer (2000) likewise anticipated this phenomenon in a paper on organizational restructuring. Further work must be done to understand more clearly the processes that underlie these observations.

Finally, complexity leadership researchers are asking whether complexity points to alternative ways to perceive leadership? There are certain informal influence and change dynamics occurring in complex systems (Plowman et al., 2007b; Schreiber and Carley, 2008), that do not bear the imprimatur of hierarchy, are not restricted to those in positions of authority, and are not necessarily imbued in the most articulate or friendly or respected people (the typical informal leadership attributions; e.g. Guastello, 2007). Uhl-Bien et al. (2007) have labelled this, adaptive leadership, while others refer to it simply as complexity; it refers to the creative, adaptive, and learning acts of individuals and groups in informal settings. However, individual and group acts are products of complex interactions and their influence is only set in motion within complex networks where individual acts interact interdependently with numerous other such acts. That is, adaptive leadership involves agentic and collectivist behaviours plus complex contexts (defined as network dynamics), and the three factors are inextricably entwined (Uhl-Bien and Marion, 2009). It is collective leadership – a collective influence forged by the combining, diverging, and elaboration of many ideas, preferences, people and groups. We further argue that this is a highly potent organizational dynamic in that it fosters emergence and change; further, it generates change that cannot be planned, thus it is a useful source of creativity within an organization (cf. Tsoukas and Chia, 2002).

EMERGING TRENDS AND DIRECTIONS

There are various emerging trends in the field of complexity leadership. Chiles et al. (2004), Uhl-Bien and Marion (2009), Uhl-Bien et al. (2007), and Hazy et al. (2007), for example, have all identified what Hedström and Swedberg (1998a) have labelled, social mechanisms, as core dynamics that complexity leadership engenders or by which it acts. Social mechanisms, or perhaps more properly, interactive dynamics, are patterns of activity; they are dynamic social processes rather than static variables (although they may include interactions among variables). The study of complexity, then, is a study of complex social mechanisms and the interactions among these mechanisms as well as their effects on system outcomes. In complexity, social mechanisms can include interaction processes, interdependency processes, network clustering processes, catalyzing processes, information flow processes, information processing processes, enabling processes, adaptive processes, organizational learning, and creativity processes (Uhl-Bien et al., 2007; Uhl-Bien and Marion, 2009).

A second trend is the emergence of complexity as a strategic leadership approach. Marion and Uhl-Bien (2007) have argued that informal dynamics are a major force in an organization's strategic response to environmental exigencies. Ralph Stacey (1995) makes a similar argument: He argues that traditional planning approaches in strategic leadership may reduce anxiety but are unable to anticipate the future and are, therefore, largely futile. He suggests that, rather than seeking equilibrium with the environment, strategic leaders seek far-from-equilibrium states in order to foster creativity and adaptability. Philip Anderson (1999) adds that a complex organization can respond rapidly to strategic environmental changes; this occurs because complex organizations are sufficiently organic to map and respond to nuanced environmental change. Karl Weick (1976) makes a similar responsiveness argument in his discussion of loose versus tight coupling. Cusumano (2001) illustrated how small groups of programmers can perceive and respond quickly to environmental demands. While these studies have established a broad framework for understanding strategic leadership from a complexity perspective, more needs to be done to hammer out details about how this is done in practice.

A third trend relates to works of House et al. (1995) and Rousseau and House (1994) and, more recently, the interest of Jerry Hunt (Hunt and Dodge, 2000), an important champion of complexity leadership prior to his death in 2008. Hunt and his colleagues Dick Osborn and Kim Boal, have encouraged this science to consider the implications of complexity science as a meso theory of leadership. Meso theory is defined by House et al. (1995) as '…a simultaneous study of at least two levels of analysis wherein (a) one or more levels concerns individual or group behavioural processes or variables, (b) one or more levels concern organizational processes or variables, and (c) the processes by which the levels of analysis are related are articulated in the form of bridging or linking, propositions' (p. 73).

A special issue of *The Leadership Quarterly* on meso theory was published in 2009 (volume 20, no. 9), and three of the articles in that edition examined complexity and meso theory. The first, by Hunt et al.

(2009) applies complexity 'order for free' notions to organizations and discusses how upper middle managers can foster and channel bottom-up emergence. The second, by Lichtenstein and Plowman (2009), proposes a link between individual level behaviour and organizational context and argues that this link exhibits a nonlinear threshold relationship; i.e. increases in contextual conditions beyond a certain level triggers cycles of emergence. The third, by Uhl-Bien and Marion (2009), argues that informal, adaptive activities (complex interactions among individuals) exist at all hierarchal levels of organization, within all embedded groups within those hierarchies, and even cut across hierarchies and groups. Thus the actions of individuals inevitably influence macro-level behaviours, and macro-level behaviours inevitably influence the actions of individuals.

Finally, yet another trend involves leadership of extreme events, such as disasters and other highly volatile events. The work here is relatively tentative, and more is being done by OT specialists than by leadership theorists. There have been discussions of this topic at a 2007 symposium at West Point and again at the 2008 Winter Conference of *Organization Science*.

CHALLENGES FOR FUTURE DEVELOPMENT

The field of complexity is developing rapidly, and each new question addressed by complexity leadership theorists spawns yet more questions, many of which have yet to be addressed. Such questions include: What is context in complexity study? Is it, for example, a physical state as was argued by contingency theorists (e.g. raw materials) or is it better defined as a network dynamic as proposed by Osborn et al. (2002) and by Uhl-Bien and Marion (2009)? How does one dismantle complexity dynamics such as terrorist networks (Marion and Uhl-Bien, 2003)? How do leaders deal with dysfunctional complexity? Can organizational conflict be explained relative to complex dynamics and if so, what is the role of complexity leadership in this process? Power and control may be anathema to complexity dynamics, yet power pervades modern organizations. How are we to deal with this problem?

A number of as yet unexplored or only tentatively explored questions revolve around the issue of complexity leadership. However, there are two issues of particular importance that must be addressed as this field moves forward.

First we need an ethical framework for the study and practice of complexity leadership. There are at least two dimensions to this issue. First, there is a need to understand the practical ethical implications of complexity leadership. Complexity is about networks and network dynamics, which, in terms of ethics, is good news and bad news. The good news is that complexity does not advocate significant power relationships, a major stimulus for unethical behaviour in organizations (Jermier, 1998), and indeed, as just noted above, one of complexity theorists' major struggles in the future will be to understand and harness the role of power and dominance in complex systems. The bad news is that it will be easy to overlook ethical problems that may arise because complexity theorists are focused on the structures of networks more than hierarchical control.

There may be, for example, unanticipated enabling actions or adaptive mechanisms that inhibit the well-being or fulfilment of organizational actors or which are systematically prejudicial to certain cultures. Complexity dynamics may make it easier for power fiefdoms to arise in informal groups. The rationale underlying complexity dynamics might enable unscrupulous managers to do harm to the environment, the community, or the people within an organization in ways we don't currently understand.

A second dimension to this issue is that the ethical rules governing traditional research may fail us when we do complexity research. Complexity research can reveal things about an organization that are not observed or knowable with traditional methodologies. For example, in a network analysis, administrator's network roles are revealed and those roles may at times be inconsistent with the administrator's personal perceptions or authority (e.g. an administrator might not be as important to the informal network as he or she believes); revealing such information could be harmful to the leader and could spill over onto innocent subordinates in the organization. In an OD analysis, revelations about the various roles that people play within the network could, inadvertently, harm relationships within that organization. (It may do the opposite as well: In a recent analysis performed by one of this paper's authors, an individual on the verge of being dismissed was found to play crucial roles in the informal dynamics of the system.) Complexity analyses cannot predict future outcomes, they can only anticipate future social mechanisms and classes of outcomes (e.g. innovation; Prigogine, 1997; Colandar, 2000). If organizational leaders use results assuming a misplaced certainty, they could do damage to the organization. Unfortunately, until we have more experience, we won't even know many of the ethical questions we need to address.

The second thing that we must tackle is increasing the number of research studies in CLT, refining research methodology for complexity dynamics, and making methodology accessible to scholars. There have been numerous theory papers written on complexity leadership theory in recent years, but there have been relatively few research papers. Some important exceptions include Chiles' et al. (2004) paper on the emergence of Branson, Missouri; the works by Plowman et al. (2007a) and Plowman et al. (2007b) on leadership and the emergence of new order in a deteriorating downtown church; Schreiber and Carley's (2008) simulation study of leadership in an armed forces unit; and Hazy's (2008) system's dynamics simulation of Intel's shift to microprocessors. While the number of research papers on complexity leadership are limited, the questions that can be asked are potentially powerful.

At present there are three dominant approaches to doing complexity research: qualitative, simulations, and power law analysis. Qualitative procedures have been relatively well-developed and disseminated, so little may need to be done towards making them accessible. Simulation procedures may not have yet reached their full potential, but nonetheless there are some very good programs available. However, simulation techniques are not widely taught in the curricula at universities and for most are only available through special workshops. McKelvey and Andriani have a chapter elsewhere in this handbook on power law analysis (fractals, scalability, power law curves), and we refer the reader to that chapter for further discussion.

The role of statistics in complexity research has yet to be established. Kathleen Carley at Carnegie Mellon, author of a complexity simulation program called Organizational Risk Analysis, advocates using statistical procedures to test the results of simulations. Some have tried using the artefacts of complex dynamics as variables in statistical analyses. Osborn and Marion (2009), for example, identified complex dynamics in international R&D alliances and analyzed an anticipated outcome – innovation – as a variable using hierarchical regression techniques. However, more study is needed to establish the role of statistics in complexity studies. More work is also needed to make scholars aware of the analytical procedures available to them in this field and to prepare them for conducting those procedures.

DISCUSSION

Possibly the greatest challenge for scholars and practitioners trying to understand and practice complexity theory and complexity leadership is in relaxing their attachment to traditional perspectives of leadership and grasping the way complexity perceives organizational behaviour. The issue is captured nicely in Snowden and Boone's (2007) statement that traditional leadership perspectives assume 'A certain amount of predictability and order exists in the world' (p. 70). That is, traditional perspectives are built around ordered perceptions of social activities, of regular, consistent relationships among variables (an effect that is true today will be true tomorrow), of control, and of future predictability. The bulk of leadership theories assume that the leader is at the centre of change, manoeuvring and motivating players and directing organizational response as issues arise. Complexity theory goes beyond all of that. Social behaviour is disordered (Stacey, 2001); its local unit of analysis is the dynamic mechanism more than the variable (Uhl-Bien and Marion, 2009); control is at best just one of many influence acts and at worst, delusional (Streatfield, 2001); anything but the immediate future is likely unpredictable (Colandar, 2000); and organizational knowledge, problems, and successes are the product of collectivist dynamics more than of any one person (Lichtenstein et al., 2006).

Complexity is a non-positivistic perspective of causal logic and methodology. Outcomes are more the products of complex interactive dynamics than variable relationships. Complexity does not entirely reject positivistic thinking (also called, methodological individualism; see Hedström and Swedberg, 1998a, b) and admits that complex systems can, in some contexts, exhibit patterned behaviour that might be analyzed statistically. Even so, there is far too much connectionism, interdependency, and holistic behaviour in social dynamics to fully embrace methodological individualism. Complexity demands that we accept unexplained social phenomenon (phase transitions, creative leaps, etc.) – a notion that is counter-intuitive to Newtonian rationality.

Scholars and practitioners, for whom the positivistic paradigm dominates their worldview, may likewise be bemused by the function of leadership in complexity dynamics. Consistent with its non-positivistic bias, complexity perceives leadership as influence in the context of interactive networks rather than as agents who direct and control change.

Moreover, like population ecology (Hannan and Freeman, 1977), there seems, at first blush, little room for agency in the complexity paradigm, so the issue of leadership looms large. Population ecology is about environmentally-induced movements in which leadership is merely another source of variation; complexity is about interaction-induced order in which leaders would seem to be merely another source of influence in a vast network of influence. However, unlike population ecologists, who cite researchers such as Salancik and Pfeffer (1977) or Weiner and Mahoney (1981) to question whether leadership plays any significant role, complexity theory is far from fatalistic on this issue. Leadership and leaders influence complex dynamics, but their role can only be understood with knowledge of the complexity context in which it occurs.

The studies of Salancik and Pfeffer (1977) and Weiner and Mahoney (1981) concluded that, after controlling for factors such as organizational size and prior productivity, there is little variation in organizational outcomes that is explained by leadership qualities. These studies were positivistic and variable-based. Neither leadership nor organizational behaviour, however, can be fully understood when a dynamic is reduced to a point of central tendency (i.e. the average leader), or when researchers ignore the processual and interdependent nature of leadership. Complexity examines interactions among leaders and organizational dynamics and seeks to understand the processes that evolve out of this interaction. Understood in this way, we can identify new perspectives of leadership and can better understand how leadership interacts with social dynamics to produce desired outcomes. Research to date on this has been promising (Chiles et al., 2004; Schreiber and Carley, 2006, 2008; Plowman et al., 2007b; Hazy, 2008) but of course more needs to be done.

CONCLUSION

We began this chapter by asking why do we need complex organization and how does leadership functions in complex organizations. Our answer to these questions, and to the issues raised in the last few paragraphs, can be summarized as follows.

Complexity itself is a hyper-interactive, adaptive, constantly morphing, networked process that is productive of surprising creativity and adaptability. Organizational complexity is useful for functioning in complex, or adaptive, environments (Heifetz, 1994). It is being used by armed forces to fight terrorism (network-centric warfare; see Cebrowski and Garstka, 1998), by Microsoft to program their exceedingly complex software programs (Cusumano, 2001) and at Sun Microsystems to enable complex problem solving in a competitive, globalized environment (Cross, 2007).

What is complexity leadership and how does it function in this context? Uhl-Bien et al. (2007) have conceptualized three forms of leadership that operate in complex organizations: adaptive leadership, enabling leadership and administrative leadership. These three forms generally represent much of what is happening in the field (albeit from different perspectives and with different emphases). Enabling leadership fosters the conditions in which complex dynamics can emerge, and is usually associated with managerial positions. We chose the word, enabling, purposefully. Complex dynamics cannot be created from a blueprint; rather, they must be allowed to emerge. Thus the role of enabling leadership is to foster rather than specify, to frame rather than build, and to guide rather than manage. Enabling leaders create conditions for complexity; they also champion promising emergent ideas, help redirect ideas that are inconsistent with organizational mission, and protect emergent ideas and complex dynamics.

Adaptive leadership represents a unique perspective that is derived from complexity theory assumptions. This is a form of leadership that is collective (i.e. a complex interactive dynamic) and acts outside of position or authority. Its influence is not unidirectional (i.e. a person with superior abilities or influence conveying coordinating wisdom to those less superior), but is rather embedded within an interactive context. That is, any given individual's act of influence bounces around in a network of influential acts, influencing others and self, and combining, converging, and adapting with other influential ideas in the system. It is a product of agency and of network dynamics, and the cumulative potential for change is significant.

Our proposals in this chapter have not diverged from the root of nearly all definitions of leadership – i.e. influence and change (Bryman, 1996). What is different about complexity is its perception of the context in which leadership is embedded and, consequently, of the manner in which leadership is conducted. It claims that leadership is not just about individuals, it is an interactive dynamic. Moreover, leadership is a function of interdependence and mechanisms rather than independent individual behaviours and variables. Perhaps most importantly, leadership that fosters change and the adaptive function in the organization happens in the informal dynamics of a system as much, or more, than in the boardrooms.

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23

A Complexity Perspective on Strategic Human Resource Management

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INTRODUCTION

Over the past three decades, research on the contribution of human resources (HR), i.e. people, and human resource management (HRM), i.e. policies and practices, to organizational effectiveness has moved from operational to strategic: from examinations of discrete HR policies and practices to consideration of how the HR strategy supports, or even drives, the strategy of the organization or sub-unit (Lengnick-Hall et al., 2009). At the core of HRM studies are questions relating HR practices to workforce attributes and behaviours, and subsequently to organizational performance outcomes, with the basic assumption that HRM matters – that the structure, design and execution of HRM practices materially affect the knowledge, capabilities and behaviour of people associated with the organization, and that better HRM translates to greater organizational effectiveness.

Strategic human resource management (SHRM) is a sub-field of HRM that emerged in the 1980s (Tichy et al., 1982) and has grown in lag-step with developments in the field of strategic management (Wright et al., 2001a). SHRM researchers draw explicit connections between firm strategy (at the corporate or business unit level) and HR strategy, and seek to explain the effects of HRM on strategy implementation as well as, more recently, strategy formulation, i.e. 'strategy making' (Snell et al., 2001). The dominant strategic management frame for articulating the contributions of SHRM is the resource-based view (RBV) (Barney, 1996; Boxall and Purcell, 2000), which posits firm resources (human, social, organizational) as central to the development of competitive advantage, and so positions human resource management in a critically important role. Despite critiques of the RBV as vague and tautological (Priem and Butler, 2001), and difficult to operationalize empirically (Delery, 1998), it has been broadly employed in strategic management research (e.g. Barney, 1991; Makadok, 2001; Sirmon et al., 2008; Lockett et al., 2009), and fully embraced by SHRM researchers as the most fruitful frame within which to express the value of HRM (Boxall, 1998; Wright et al., 2001a; Boxall et al., 2007).

Colbert (2004) sought to overcome critiques of the RBV by identifying the resonance between critical-but-difficult aspects of the RBV and core concepts of 'complexity thinking'; then exploring the implications of integrating 'complexity principles' – generally common features guiding the development of complex systems – into the HR system. There is a paradox at the core of the RBV: those features of resources which create and protect the essence of a sustained resource-based advantage (i.e. characterized by causal ambiguity, based upon socially embedded, complex knowledge and capabilities), also make them inscrutable and unpredictable, and therefore difficult if not impossible to engineer and manage. The clear parallels between the RBV and complexity thinking point to the latter's potential to inform the former and, from this, to derive implications for Strategic HRM.

In this chapter, we consider the implications for SHRM of a particular thread of complexity thinking, namely a *complex responsive processes* (CRP) perspective as articulated by Stacey and colleagues (Stacey et al., 2000; Griffin, 2001; Streatfield, 2001; Fonseca, 2002; Stacey 2003). The key questions for scholars of SHRM and the RBV are process questions concerning how a resource-based advantage comes into being, and how a firm builds 'competitive potential', i.e. the latent capacity for innovation that resides in the human resources of the organization. However, in neither field have researchers been very successful at penetrating the processes at the centre of 'emergent innovation' – the means through which competitive potential is realized as real innovation in the generation and delivery of products or services. The CRP perspective is focused on process, and aims to explain how novelty emerges. It differs fundamentally – on ontological, epistemological and methodological grounds – from alternate, more developed system-oriented interpretations of complexity thinking applied to organizations, so offers much potential for developing novel insights for SHRM.

This chapter proceeds as follows: first we highlight the key questions in HRM, and situate SHRM as a sub-field of the larger discipline. HRM is a mature, wide-ranging field of study, so a comprehensive review is beyond our scope; rather we delineate central concerns and draw upon excellent reviews of the field to focus on the most contemporary challenges, in particular the role of HRM in building competitive potential and in driving organizational strategy and innovation (Snell et al., 2001). We then briefly recapitulate the points of affinity between the resource-based view in strategy and concepts from complexity thinking (Colbert, 2004), in order to focus on the strategic aspects of HRM, and to motivate the discussion to follow on the potential offered by a complex responsive processes view of organizational strategy and change. We then provide an overview of CRP concepts to delineate the distinctive contribution of a CRP view as compared to traditional organization theory. We conclude with a discussion of a CRP view's implications for SHRM.

STRATEGIC HUMAN RESOURCE MANAGEMENT: KEY QUESTIONS

Strategic human resource management is focused on the overarching HR strategies of an organization or sub-unit, and their impact on performance (Boxall et al., 2007). Some basic questions pertinent to the practice of SHRM are: What are the effects of HR practices on the development of a firm's human resources? What are critical strategic human resources? Which HR practices lead to greater organizational performance? To what degree is that contingent upon firm strategy? How does a firm ensure that its HR practices fit with its strategy, and that there is enough flexibility in the HR system to be able to adapt, should the business strategy change? How can we ensure that individual HR practices fit with one another, and do not work at cross purposes? Must the attributes of a firm's base of human resources always align to a prior determined strategy, or can its stock of skills, knowledge and interactions drive strategic direction? The key constructs and central debates in SHRM have grown from these questions: best-practices vs. fit (Becker and Gerhart, 1996): horizontal fit and vertical fit (Schuler and Jackson, 1987; Delery, 1998); fit and flexibility (Wright and Snell, 1998); strategy contingent HR systems (Lengnick-Hall and Lengnick-Hall, 1988; Boxall and Purcell, 2000): and control-exerting vs. creativity-enhancing aspects of HR systems (Snell et al., 1996; Heraty, 2004; Hayton, 2005).

A recent review of the evolution of the field of SHRM (Lengnick-Hall et al., 2009) surfaced seven themes across time in the SHRM literature: (1) explaining contingency perspectives and fit (e.g. Baird and Meshoulam, 1988; Wright et al., 1995), (2) shifting from a focus on managing people to creating strategic contributions (e.g. Wright and Snell, 1991; Huselid, 1995; Hatch and Dyer, 2004), (3) elaborating HR system components and structure (e.g. Lepak and Snell, 2002; Arthur and Boyles, 2007), (4) expanding the scope of SHRM beyond organizational boundaries (e.g. Schuler and MacMillan, 1984; Gardner, 2005), (5) achieving HR implementation and execution (e.g. Becker and Huselid, 1999; Boswell, 2006), (6) measuring outcomes of SHRM (e.g. Rogers and Wright, 1998; Colakoglu et al., 2006), and (7) evaluating methodological issues (Gerhart et al., 2000; Wright, et al., 2001b). That these themes range comprehensively from examining specific discrete HR practices, to more strategically oriented considerations, to structural aspects of the HR system, to implementation and measurement issues, illustrates the relative maturity of the HRM discipline.

Three eras of strategic HRM

Other reviewers of the field outlined three 'eras' of HR strategy characterized by the central focus of research in each chronological era (Snell et al., 2001), and concluded that the challenges in SHRM are shifting fundamentally, founded on new bases for competitive advantage in the knowledge/ information era.

Up to the 1970s, a focus on *person–job fit* was the dominant organizing frame for HRM scholarship and practice. From roots in the industrial revolution and especially in heavy manufacturing in automobiles, steel, and rail, corporate strategies focused on expansion and vertical integration to keep pace with the growing demands of a burgeoning and prosperous post-war population. The keys to competitiveness were stability, efficiency, and productivity, achieved through a division of labour, specialization, and work standardization. Workers were recruited and minimally trained to fit the well-defined job tasks, and were easily replaceable. Analytic HR methods were paramount and job analysis was the foundation for all HR activities, providing a breakdown of tasks, duties, responsibilities and the requisite skills, knowledge, abilities to perform them.

The 1980s saw a shift to new organizational challenges of global competition, automation, and total quality management, and the primary focus of HR research and practice moved from the 'micro' HR concerns of *person–job fit*, to more 'macro' consideration of *HR systemic fit* – ensuring that HR policies and practices were complementary and mutually reinforcing towards common organizational objectives. Competition for high quality job candidates meant that, for example, development, compensation, and appraisal systems must align – what was termed 'internal (or horizontal) fit' of HR systems. Questions of 'external (or vertical) fit' examined whether HR practices fit with the stage of development of the firm (growing with it) and aligned with the strategy. In both the *person–job fit* era and the *systemic fit* era, HR strategy followed business strategy, and was primarily concerned with issues of successful strategy implementation. Although these are presented as chronological eras, they are not mutually distinct, and represent only a shift in emphasis: ideas and practices centred on *person–job fit* and *systemic fit* HR are still being practiced, but their importance as a strategic differentiator for the typical firm has diminished.

The expansion in the past two decades of globalized systems of manufacture and trade, driven by exponential advances in information technology and management, means that the bases for competition are shifting significantly towards intangible organizational resources such as knowledge, innovation, learning, leadership, and culture (Kaplan and Norton, 2004). All of these intangible resources are embodied in people or are embedded in social networks within the organization, and this is a highly significant shift: these assets are often characterized as the 'human capital' of the organization, resonating with notions of financial capital, i.e. the traditional accounting view of capital as land and equipment. However, human capital resides in people and in relationships and routines linking them – which means that a key strategic resource is not actually 'owned' by the firm. The old tools of HRM, job analysis and task breakdown, are not strategically central in this era; rather the emphasis is now on processes for building and deploying human capital. This is the era of *competitive potential* – the task of HR is to build a pool of latent potential to not only implement strategy, but to initiate and formulate strategy as well. In other words, the HR function is no longer just a 'strategy-taker', but has become a key 'strategy-maker' – a key driver of corporate direction. In the era of *competitive potential*, HR strategy is more important than ever – HR strategy and business strategy have converged (Snell et al., 2001).

Competitive potential, SHRM and the resource based view of strategy

Competitive potential has moved to the foreground in importance in SHRM, but is not a new concept within strategy research or the resource-based view of competitive advantage. Economist Edith Penrose, whose work 50 years ago is widely regarded as the genesis of the RBV, was interested in the *process* of firm growth and its relation to sustained advantage. She proposed that:

> … the availability of unused productive services within it create the productive opportunity of a given firm. Unused productive services are, for the enterprising firm, at the same time a challenge to innovate, an incentive to expand, and a source of competitive advantage. (Penrose, 1959: 85)

In its original conception, the RBV held that a firm's resource base contains not only adaptive potential, but also creative potential – both of which are captured in the more recent idea of competitive potential. The 'unused productive services', which in SHRM terms means the knowledge, skills, and behavioral dynamics of individuals and groups, are forces for creativity, innovation, growth, and relative industry advantage. To be of strategic value, Human Resource Management practices should be focused on building and leveraging both creative and adaptive sources of competitive advantage: the latent creative potential in the organization's human resource pool, and the idiosyncratic capabilities which serve to realize that potential, and help the organization adapt to and thrive within its operating environment.

The RBV has been critiqued as a static concept, unable to adequately capture the nature of a dynamic business environment (Eisenhardt and Martin, 2000; Priem and Butler, 2001), and therefore more recent work in the RBV stream emphasizes 'dynamic capabilities' (Helfat, 1997; Teece et al., 1997; Eisenhardt and Martin, 2000; Makadok, 2001; Zahra and George, 2002), which are the organizational and strategic processes through which managers convert resources into new productive assets in the context of changing markets (Galunic and Eisenhart, 2001). There have been several efforts to identify and prescribe dynamic capabilities in both theoretical terms (Teece et al., 1997; Luo, 2000; Zott, 2003), and through empirical studies (e.g. Helfat, 1997, 2000; Griffith and Harvey, 2001; Rindova and Kotha, 2001). In an extensive review of the dynamic capabilities literature, Wang and Ahmed (2007) defined dynamic capabilities as:

> … a firm's behavioural orientation constantly to integrate, reconfigure, renew and recreate its resources and capabilities and, most importantly, upgrade and reconstruct its core capabilities in response to the changing environment to attain and sustain competitive advantage. By this definition, we first argue that dynamic capabilities are not simply processes [i.e. codified management processes], but embedded in processes. (p. 35)

They also derive three main components of dynamic capabilities: adaptive capacity (ability to identify and capitalize on emerging market opportunities), absorptive capacity (ability to recognize and assimilate new commercially useful information) and innovative capacity (ability to develop new products and markets through aligning strategic orientation with innovative behaviours and processes). The idea of adaptive capacity mirrors Penrose's (1959) concept of adaptive potential, and innovative capacity reflects her idea of creative potential. However the organizational dynamics driving the development of these factors remains unclear, although they are understood to be path-dependent and complex in nature (Wang and Ahmed, 2007). From Penrose in the 1950s to recent work in dynamic capabilities, the adaptive *and* creative components of the RBV are clearly established as strategically important, if not well defined, but they have only more recently moved to the centre of SHRM in the era of competitive potential. The actual process of how competitive potential becomes 'emergent novelty' remains opaque. Throughout the large body of scholarly writing in the RBV, in strategy and with specific respect to SHRM, there have been a few key aspects of resources widely acknowledged to be both critically important, and exceedingly difficult to adequately represent. This is primarily due to the apparently paradoxical internal logic of the RBV, at least as it has been framed to date: the strategic value of firm resources lies in their inherent complexity, and attempts to causally unravel that complexity are counterproductive, if not futile. Wright et al. (2001: 709) conclude that taking RBV deeper into SHRM research 'requires recognizing that the inimitability of [organizational] competencies may stem from unobservability (e.g. causal ambiguity), complexity (e.g. social complexity), and/or time compression diseconomies (e.g. path dependence)'.

We argue that such issues with the RBV arise when one thinks in systemic terms, rather than in process terms, and that insights from a process-focused view of complexity can help to reframe the difficult aspects of the RBV. We begin our argument by connecting four critical-but-difficult aspects of the RBV to features of complex systems (see Colbert, 2004 for a full explication of these aspects in the RBV literature): a focus on the *creative* as well as the *adaptive* aspects of the RBV; the centrality of *complexity* and *causal ambiguity* to its logic; the importance of *disequilibrium*, *dynamism*, and *path dependence*; and the idea of *system-level resources*. All of these are deemed essential to a sustained resource-based advantage, but are also critiqued as difficult, obtuse and impenetrable to organizational researchers and managers. Yet each can also be related to foundational concepts in the study of complexity. This congruence (see Table 23.1) suggests that transferring ideas from complexity science to the RBV and SHRM offers the potential for novel insight, particularly given that SHRM researchers have explicitly called for a focus on these organizational phenomena to advance the development of the field.

In one of the few works comprehensively linking complexity and HRM, Colbert (2004) draws on this congruence and on the work of Kelly (1994) to outline a framework for injecting complexity principles into the design architecture of the HR system. Here we consider a different complexity science-inspired conception of organizations, not as complex systems but, rather, as *complex responsive processes* (Stacey, 2001), in order to address directly the process questions in SHRM.

Table 23.1 Parallels between the resource-based view of the firm and complex adaptive systems*

Key features	*Resource-based view of the firm*	*Complex adaptive systems*
Creativity/adaptability	Competitive advantage grows from latent creative potential embedded in firm resources	Complex adaptive systems learn and create new responses to their contextual environment
Complexity and ambiguity	Inimitability arises from social complexity and causal ambiguity	Complex adaptive systems are comprised of agents linked through complex interrelationships that are nonlinear, non-deterministic, and unpredictable
Disequilibrium, dynamism, path dependence	Complex relationships build over time, are historically dependent; disequilibrium is the creative state; dynamism, process issues are paramount.	Complex adaptive systems move towards and thrive at far-from-equilibrium states; equilibrium leads to stagnation, decline, and death; history matters; paths unfold irreversibly through time
System-level phenomena	Some key strategic resources are intangible, and exist only at the system-level, emerging from and existing in relationships between lower-level resources	Some features and properties of complex adaptive systems emerge, and only exist, at the system-level, in the dynamic relationships *between* things.

* Adapted from Colbert (2004).

Key role for HRM: building competitive potential and innovative capacity

Building competitive potential in human systems necessarily 'places a premium on knowledge-based assets and the processes that underlie learning and innovation' (Snell et al., 2001: 634). Innovation can be seen as simply the emergence of useful novelty – new products, services, knowledge, routines, or capabilities, all rooted in new ways of thinking and talking about the organization and its activities. Similarly, organizational strategy can be seen as, essentially, innovation in value creation: the development of new forms of value for stakeholders and of means to deliver that value. If HRM is to be a 'maker', and not just a 'taker' of organizational strategy, then the core task of HRM is to foster the potential for creative innovation inside the firm.

Innovation in organizations is often characterized as a process through which ideas are converted into products or services; or are realized as new organizational routines or structures (Cooper et al., 1999; Adams et al., 2006). What is less understood is how novel ideas emerge in the first instance. Fonseca (2002) traced the roots of mainstream management conceptions of innovation to two streams of economic theory. Classical and neoclassical economics focused on the functioning of markets as resource allocation mechanisms, and innovation is an exogenous variable in the production function, an independent factor of organizational or technological change, most often displacing labour with capital and disrupting market forces temporarily until a new equilibrium is established. The second stream, evolutionary economics (based on Schumpter, 1934), dealt with the processes of economic growth, and depended on a heroic, intuitive entrepreneur to challenge existing ways of thinking and to forge a vision, and to pursue it through political processes. In both of these streams the innovation appears fully formed, and then is put into play. As a result, the phases identified in 'innovation management' processes begin after the innovation has already emerged. Some innovation theory makes reference to an 'innovation culture' in general terms (Cooper and Kleinschmidt, 1995; Burgelman et al., 2004), but examinations of innovation processes are generally about managing the innovation once it has emerged, or at best, running formalized brainstorm idea generation processes at the front end.

Thus, SHRM researchers have pointed to the need to focus on the root processes underlying innovation, i.e. those that generate novel ideas, and in particular on how the quality of participation of organizational members affects these:

> … we need less research on the control attributes of SHRM and more research on how participative systems can increase the potential value of and impact of employees on firm performance. If human capital is valuable, we have to learn how to unleash that value. (Snell et al., 1996: 65)

The core strategic question for SHRM therefore becomes: how is competitive potential, or the innovative capacity of the organization, encouraged to thrive and be realized as emergent novelty? Complexity thinking, particularly theorizing of complex responsive processes, deals with this question directly.

COMPLEX RESPONSIVE PROCESSES

The many facets of complexity science and complexity thinking as applied to management are highlighted elsewhere (e.g. Maguire et al., 2006) as well as throughout this volume, so we limit ourselves here to identifying a few basic ideas in order to introduce and situate the concept of complex responsive processes, before discussing its important implications for HRM.

Complexity science generally denotes a wide-ranging body of work built on such fields as chaos theory (Lorenz, 1963; Gleick, 1987), cybernetics (Weiner, 1948; Ashby, 1956; Hayles, 2000), and dynamic systems theory (Jantsch, 1980; Prigogine and Stengers, 1984; Kauffman, 1992). It includes the study of *complex adaptive systems (CAS)*, which is a system comprised of 'a large number of agents, each of which behaves according to its own principles of local interaction' such that '[n]o individual agent, or group of agents, determines the patterns of behavior that the system as a whole displays, or how those patterns evolve, and neither does anything outside the system' (Stacey et al., 2000: 106). Its components (i.e. 'agents') operate with some measure of autonomy, as well as in relation to other system components, i.e. both independently and interdependently; and their interactions give rise to system-level emergent properties that are irreducible, exist only in these underlying relationships, and are unpredictable in advance of their manifestation. The agents self-organize into patterns that give the overall system its shape and identity. McKelvey (2004) has identified the central focus of complexity science as the study, not of complexity *per se*, but of order-creation dynamics that give rise to new forms, such as those in a CAS.

In interpretive, metaphorical applications of complexity science in management, the human analogue of a complex adaptive system is typically assumed to be a group of individuals, i.e. with individual humans as the CAS' agents (Stacey, 2003). The analogue for self-organization is people forming into groups, teams, or organizations; while the system programmer, or scientist, is taken to be the manager, who somehow stands outside the system and is able to alter conditions so that the dynamics are brought to 'the edge of chaos' (i.e. where the system is at once both stable and unstable, and is maximally adaptive and creative).

Because the critical questions in Strategic HRM focus on process, and in particular on the processes that build competitive potential to create a resource-based advantage, we take a process view of complexity for this chapter to shine light from a different angle on the challenges in SHRM. Stacey and colleagues (Griffin et al., 1998; Stacey et al., 2000; Fonseca, 2002; Shaw, 2002; Stacey, 2003) have elucidated extended and coherent interpretations of organizations as 'complex responsive processes' (in contrast to the more popular 'complex adaptive systems' analogy), with the aim of describing the processes that give rise to 'emergent novelty', which then translates into innovation and organizational strategy. Although the concepts within CRP thinking are rather abstract, the rigorous treatment given to the full analogical transference of complexity concepts to organizations is compelling and persuasive, and carefully grounded in consistent ontological terms.

A complex responsive processes (CRP) view describes organizations as the patterning of relationships among people; the focus is on how processes of communicative interaction self-organize into dominant (i.e. organizationally legitimate) and shadow (i.e. organizationally illegitimate or subversive) themes that give and perpetuate meaning to organizational life, and how those themes and patterns change in unpredictable ways. 'Knowledge' in this view refers not to something that is codified, but rather to meaning which is socially constructed and continually recreated in the living present, constrained by but also simultaneously shaping power relations among individuals. Themes are recursively formed and perpetuated through narrative, and there is at the same time the potential for new propositional meaning themes to emerge. The core process for both narrative and propositional themes is conversation – free flowing, turn-taking exchange of symbols between humans in the living present. Because a central but ill understood feature of complex adaptive systems is their paradoxical ability to simultaneously self-perpetuate yet adaptively transform, i.e. to enable novelty to emerge with no controlling plan or pre-determined path, a complex responsive processes view endeavours to explain emergent novelty in organizations from a process perspective.

Under a CRP view, the analogue for the interaction among agents in a complex system (or for the digital code in computer simulations of CAS) is the patterning of symbols people use to communicate with each other into themes that order relations. Human communication symbols interact through conversation (broadly defined, including verbal and semiotic exchanges), and arrangements of those symbols take the form of themes of meaning, stories and propositions:

> In other words, the analogue of agents is the themes organizing conversation communication, and power relations. What is organising itself, therefore, is not individuals but the pattern of their relations in communicational and power terms in the public vocal arena, and at the same time, in the silent, private arena that is mind. The analogue of a complex adaptive system in human terms is then the self-organising processes of communicating in power relations. (Stacey, 2003: 332)

Innovation is the emergence of novelty; it is 'not thought of in terms of the action of adopting some well-defined novelty, but as the process of developing that novelty' (Fonseca, 2002: 17). A complex responsive processes view is a way of thinking about complex systems as interactions between diverse entities that amplifies differences to produce emergent novelty (Stacey et al., 2000). When there is diversity in meaning comprehension – which in some instances may be labelled by participants as misunderstanding – there is the potential for new ways of thinking, talking and acting to emerge.

Four questions that distinguish a complex responsive processes view

Here we present a brief summation of a CRP view organized under four core questions offered by Stacey (2003) to differentiate systems theories from a CRP perspective, in order to frame the implications for the challenges in Strategic HRM, which in general terms involves a refocusing of attention toward important qualities of organization. The four questions are: What is the assumed nature of human interaction? What are the implicit assumptions about human nature? What is the methodological stance, and by extension, the role of the manager? And how is paradox approached? The key distinctions between a systemic view and a complex responsive processes view of organizations are summarized in Table 23.2.

Table 23.2 Distinctions between systemic view and a complex responsive processes view*

Four questions	*Systemic view of organizations (e.g. strategic choice, learning organization, open systems)*	*Complex responsive processes view of organizations*
Nature of interaction	Dualist: Interactions between people create 'the system'; people then interact with the reified system, and are subjected to its larger purpose	Iterated processes of relating, manifested in narrative themes (who we are) and propositional themes (who we might be); simultaneous formation of power relations
View of human nature	Both the individual and the social are seen as separate from one another, and are drawn as interacting in time and space; relationships are drawn between individual schema and socially constructed schema	Neither the individual nor group identity is prior, but are simultaneously constructed through ongoing conversation, both public and vocal and private and silent
Methodology: position of the manager	'The system' is something bounded and defined that we can stand apart from to manage or study; manager seeks leverage points at which to intervene and control system behaviour	Managers are full participants in the conversational processes that shape organizational dynamics; cannot control dynamics, but only influence the bounds of instability
View of paradox	Resolve contradictions and remove paradoxical tensions, as traditional theories of organizational dynamics are equilibrium-seeking, with stability or gap-closing as a core goal	Embrace tension to drive forward iterative dynamic of ongoing meaning creation; paradox is essential for generating creative novelty, which arises from the tension between legitimate and shadow themes

*Constructed from Stacey (2003)

Nature of human interaction

Dominant theories of organizational dynamics (where 'dynamics' refers to the pattern of movement over time), such as strategic choice theory, learning organization theory, and open systems theory, take a *systemic* theory of interaction: interactions between people are assumed to create a whole ('the system', the boundaries of which are arbitrarily defined, often as the working group, the department, the unit, or the organization); people are then seen as parts of this whole, and are in some way subjected to the purpose of the whole. Attention is on the behavior of the macro system, and the notion of micro-diversity is largely ignored, which is problematic since micro-diversity is the key driver of innovation and adaptation in complexity thinking in the natural sciences (Prigogine and Stengers, 1984; Kauffman, 1995).

Under a systemic complexity view of human systems, the organization–individual relationship is most often taken as the system–agent analogue in biological complex adaptive systems (e.g. Morgan, 1996; Brown and Eisenhardt, 1997, 1998; Morel and Ramanujam, 1999). Yet human understanding, intention, and action are highly complex notions in themselves; therefore to aggregate at the level of the individual person is to draw an arbitrary conception of 'the agent' for the sake of metaphorical convenience. A systemic view offers limited help in explaining the emergence of genuine novelty and innovation (Fonseca, 2002).

View of human nature

Stacey (2003) drew on the philosophy of Hegel and the sociology of Mead (1934) and Elias (1991, originally published in German, 1939) to outline a 'process sociology' perspective of human interaction and meaning construction, and identified a compelling similarity between the dynamics described in 1930s process sociology and those represented in heterogeneous-agent computer-based models of complex interaction developed in the complexity sciences, both in organic simulations (Ray, 1992) and in models of economic systems (Allen, 1998). Process sociology theorists posit that individual personality and society emerge simultaneously: each defines and is defined by the other at once, and neither can reasonably be argued to be prior cause of the other (Elias, 1991).

This view is clearly distinguishable from both cognitive and sociological perspectives in human psychology. Cognition theory holds the individual as prior to the group; the individual mind is the locus of meaning construction, or sensemaking (Weick, 1995). Groups are seen as collectives of individuals, and those groups might then affect how individuals behave (Stacey, 2003). Social constructivism places the social level as the prior and primary shaping force of individual personality. Cognition and sociological perspectives are both rooted in system thinking, where relationships are drawn between individual schema, or structural maps of meaning, and social schema. Both the individual and the social are seen as separate from one another, and are drawn as interacting in time and space. In process sociology, 'individual' and 'group' are constructed simultaneously – a group cannot exist prior to an individual, and individual identities always emerge and are defined in a social context.

Conversation is the core process for the ongoing creation (and transformative, innovative re-creation) of meaning and identity, therefore a CRP view re-focuses attention on the quality of conversational life in an organization.

Methodological stance and the implicit role of the manager

System thinking asks us to consider a system as something bounded and defined that we can stand apart from to manage or study. Strategic choice (Hofer and Schendel, 1978; Porter, 1980) and learning organization theorists (Senge, 1990) draw schematic maps to characterize system dynamics, and to find leverage points for managers to intervene and control. Likewise with many applications of complexity thinking to organizations; complex adaptive systems management theorists (e.g. Morgan, 1996; Brown and Eisenhardt, 1998) often place the practicing manager outside the system as observer and controller, and ascribe the manager undue agency and control over complex organizational processes. A complex responsive process perspective assumes that the manager is one actor in the mix, and patterns of interaction form and are formed by ongoing exchange of meaning symbols and power relating. With a focus on pure process and a withdrawal from spatial metaphors, the individual cannot stand apart from the system. Individual and group are the singular and plural form of the same phenomenon, relating. 'individual mind' and 'collective mind' are constructed simultaneously through ongoing conversational exchange of narrative themes (framing and describing how things are) and propositional themes (framing and suggesting how things could be).

A CRP view posits that managerial 'control' of organizational dynamics is impossible, and that patterns of relating self-organize. That does not mean we ignore organizational hierarchies, or that the manager or CEO is disempowered; only that the path dynamic (the pattern of movement over time) is co-created by all involved.

Approach to paradox

An apparent paradox can be treated as a *dichotomy* (an either/or choice of action – e.g. offer high quality products or drive costs and price down), as a *dilemma* (a choice between two unattractive alternatives – e.g. raise prices or lay off staff to meet financial goals), or as a *duality* (a 'both … and' resolution to a contradiction – e.g. 'both thinking globally and acting locally' in a mass-customization manufacturing model). In all of these conceptions, the aim is to resolve the contradiction and remove the tension, as traditional theories of organizational dynamics are equilibrium-seeking, with stability or gap-closing as a core goal. The first two are binary choices, and a dualism locates the two poles of the contradiction in different spaces or times – thinking in one mode and acting in another, keeping both, and resolving the contradiction.

A true *paradox* is defined as 'a state in which two diametrically opposing forces/ideas are simultaneously present, neither of which can ever be resolved or eliminated' (Stacey, 2003: 11), with no possibility of choice (e.g. individuals in an organization may desire freedom, chance, and the thrill of uncertainty, but also crave security, order and discipline). Real paradox and the attendant tension is a key driver of creativity and novelty. A complex responsive processes view embraces such tension, and accepts that it can never fully be resolved, but can drive forward an iterative dynamic of ongoing meaning creation in a Hegelian dialectical sense, where competing ideas remain, but the quality of their tension transforms their meaning, and each is seen differently.

Prescriptive challenges in complexity: 'managing emergence?'

Theorists in the CRP school resist offering prescriptions for managing, with the argument that each context is unique, path-dependent, and self-organizing: 'a theory that focuses attention on self-organising processes and emergent outcomes can hardly yield general prescriptions on how that self-organisation should proceed and what should emerge from it. The theory would be proposing to do the opposite of what it is explaining' (Stacey, 2003: 415). Fonseca (2002: 120) concludes: 'conversational activity in any organization cannot be engineered. This means that innovation cannot be managed'.

We think it is possible to embrace the descriptive tenets of the CRP view as outlined in the points above, and still allow room for useful recommendations to managers. If knowledge-as-meaning is continually renewed and transformed through conversation that is bounded by and simultaneously formative of power relations, then managers do exercise some measure of influence on the tenor and shape of themes in those conversations, and on communicative processes that determine which are legitimate and shadow themes. It may be no more influence than any other member (though one could argue it often is, through structural power differential and influence), but it is certainly no less. While resisting specific hard prescriptions, Stacey did offer ideas on the implications for organizations towards refocusing attention on certain qualities of organizational process, with some thoughts on the role for managers. There is considerable interplay and overlap among these qualities, and so we will combine some and consider four here: the quality of participation and interaction in conversation; the quality of anxiety and how it is lived with; the quality of diversity; and the quality of unpredictability and paradox. In the discussion following we extend those implications to managerial competencies and to the role of Strategic HRM processes. By HRM processes here we mean the ongoing activities of the HRM system: the principles, policies and practices as designed and deployed by HRM practitioners (Colbert, 2004).

IMPLICATIONS OF THE CRP VIEW: MANAGEMENT COMPETENCIES AND HR PROCESSES

Next we consider Stacey's four qualities of organization and extend the implications to identifying (1) the role of managers; (2) critical management competencies; (3) the role of HRM in helping to develop those competencies; and (4) the role for the HR practitioner, and the relevant HR processes to deploy for helping to focus attention on the qualities important to fostering innovation. We use the term 'manager' here to mean anyone in a formal leadership role, from CEO to the first line. 'HR practitioner' refers to those who design and steward the operation of the HR processes of the firm, which could include both HR professionals, and line managers depending on the size and design of the organization. Table 23.3 summarizes the four qualities and their implications.

Table 23.3 Implications of a complex responsive processes view for managers and the HR function

*A complex responsive processes view re-focusing attention**	*Implications for management competencies (and for HR leadership development)*	*Implications for the HR function*
Quality of participation in conversational life of the organization Attention to the thematic patterning of interaction: patterning of power relations, inclusion and exclusion, ideological themes emerging	**Manager as process consultant** Observing and feeding back thematic patterns; unblocking stuck conversational themes **Relevant competencies:** Social process consultation Emotional intelligence Critical thinking	**HR practitioner as process consultant** Providing high level process consultation services and leadership development **Relevant SHRM processes:** Process consultation Talent management Executive coaching
Quality of anxiety and how it is lived with Attention to threatened identities as innovations arise; to feelings of incompetence in the face of uncertainty	**Manager as holder of anxiety** Reflecting on the sources of anxiety in the living present; building trust and confidence in change and oneself **Relevant competencies:** Reflective practice Comfort with ambiguity Counselling	**HR practitioner as holder of anxiety** Identifying organization wide sources of anxiety and trust **Relevant SHRM processes:** Inclusive change management Employee relations
Quality of diversity Attention to the importance of unofficial ideologies that undermine current power relations	**Manager as moderator of challenge and conflict** Noticing the tension between legitimate themes and shadow themes, and how inclusion and exclusion occurs **Relevant competencies:** Critical thinking – surfacing assumptions Integrative thinking	**HR practitioner as moderator of challenge and conflict** Implementing formal and informal opportunities for generative and strategic dialogue **Relevant SHRM processes:** Appreciative inquiry 'Fishbowl' management feedback
Quality of unpredictability and paradox Attention to how unpredictability is tolerated and how paradox is a source of generative tension	**Manager as leader of emergent enquiry** Accepting that unpredictability is inseparable from creativity; holding paradox open and leading inquiry on it **Relevant competencies:** Integrative thinking Triple loop learning enquiry	**HR practitioner as leader of emergent enquiry** Engaging internal and external stakeholders in surfacing and generating paradoxical creative tension **Relevant SHRM processes:** Stakeholder engagement Radical transactiveness Triple loop learning enquiry

*Column 1 adapted from Stacey (2003).

Quality of participation in conversational life: Managers and HR practitioners as process consultants

The CRP perspective directs attention towards the thematic patterning of interaction, such as the patterning of power relations, inclusion and exclusion, ideological themes emerging, and shifts in patterns of identity that can give rise to anxiety. Relationships are organized in conversations that form and are formed by the power relations between people. Organizations can only change when the themes that order conversations and power relations change, and organizational learning represents change in these themes.

Process consultation (Schein, 1998) involves attending to the patterns, base assumptions and inferences emerging in meaning making, i.e. conversational exchanges, and reflexively surfacing some for feedback into the ongoing process. Once the exclusive domain of organization development practitioners and psychotherapists, process consultation has moved to being a core organizational competency for innovation.

A competent manager is one who is sensitive to the themes that are organizing conversational relating and to rhetorical ploys that can block the emergence of new conversational themes, and who participates to assist in altering themes. They observe and feed back thematic patterns, unblocking stuck conversational themes. Specific relevant competencies are social process consultation (Schein, 1998), emotional intelligence (Goleman, 2005), and critical thinking skills, i.e. the ability to identify dominant claims and surface basic assumptions – both reality assumptions about how we think the world works, and values assumptions about the way we think it ought (Dyer, 2006).

The HRM practitioner can also act as process consultant by deploying appropriate HR processes. Many HR functions offer high level process consultation in services from strategy development to business planning to conflict moderation. Such formalized consultation can serve to enrich the conversational life of the organization in formal settings, and can also set the tenor for how conversational patterns are noticed, which can carry over to more informal settings. For example, a manager may draw upon in-house facilitation services to help bring formal process to a conflict situation. A skilled process facilitation consultant can help to surface issues, underlying assumptions and causes of conflict, with attention to full, constructive participation by all involved, thereby modelling positive dialogue techniques for both the manager and the team. The HR processes also contribute significantly to leadership development through training, talent management (Lewis and Heckman, 2006) and executive coaching, and by building process consultation skills into leadership competency profiles and assessments.

Quality of anxiety and how it is lived with: Managers and HR practitioners as holders of anxiety

The CRP perspective focuses attention on the importance of free-flowing conversation in which people are able to search for new meaning. Themes organizing the experience of relating are expressed in vocal, public conversations between people, and also in the silent, private conversations that are individual minds. New ways of talking publicly are reflected in new ways of individuals making sense of themselves, and anxiety is inevitably associated with shifts in themes that organize the experience of relating, as individual and collective identities are threatened. The uncertainty that comes with creativity can give rise to anxiety, even shame at feelings of incompetence. The capacity for living with anxiety is critical to organizational change and innovation.

Innovation and competitive potential depends on managers who are capable of reflecting on the sources of anxiety in the living present, and of building trust and confidence in change and in others. Reflective practice (Raelin, 2002), and comfort with ambiguity through mindfulness (Kabat-Zinn, 1994), along with the skill to counsel others, are therefore important management competencies.

The HRM practitioner can help organizational members live with anxiety by identifying organization-wide sources of anxiety, and embedding trust-building processes into change management processes and employee relations processes. Inclusive change processes with high involvement in exploration, direction setting and implementation planning can help to hold feelings of anxiety open to allow innovation to surface in ways of conversing, power relating, and identity construction. For example, when leaders of an organization or a sub-division are seeking to strategically re-orient direction, they can do so with high involvement methods, such as a 'future search conference' (Weisbord, 2005), in which a whole unit of 500 people can be included in explorations of past performance and culture, current state, and future possibilities, with all of the attendant implications. Transparency and inclusion can surface anxiety, and channel it towards innovative re-invention rather than destructive conflict.

Quality of diversity: Managers and HR practitioners as moderators of challenge and conflict

The possibility of the emergent new lies in the inherent property of nonlinear interaction to amplify small differences, and innovation emerges in the amplification of the diversity between participants in interactive communication, even when that diversity is quite small: 'The processes that pattern our experience of being together are also the processes in which emerges the potential transformation of the pattern' (Fonseca, 2002: 79). A CRP view therefore focuses attention on the importance of diversity in meaning (versus a culture of sameness), and on unofficial ideologies that can undermine current power relations.

While competent managers are not necessarily those who incite revolution and revolt, a critical skill lies in noticing, tolerating and holding the tension between legitimate themes and shadow themes, and observing how inclusion and exclusion occurs – what is acceptable to discuss or not, and more important, how that gets decided. Here again, critical thinking skills are essential for surfacing assumptions, and integrative thinking skills (Martin, 2007) are necessary to hold apparent opposites in creative tension.

HRM functions can institutionalize tolerance for challenge and conflict by implementing formal and informal opportunities for *generative* and *strategic dialogue*. *Generative dialogue* aims to unearth underlying assumptions and generate shared frames of meaning among organizational members (Banathy, 1996), and is a precursor to *strategic dialogue*, which is focused on identifying directions and actions for the organization (Liedtka, 2001). 'Fishbowl' management feedback processes (Kane, 1995) where leaders receive constructive feedback in a structured format, balanced with Appreciative Inquiry (Barrett and Fry, 2005) processes to generate positive feedback effects, can be useful approaches to encourage diversity of opinion, and a positive approach to diverse opinions. For example, weekly meetings to review organizational performance metrics could include time to reflect and open dialogue on strategic directions and specific initiatives, with added attention to dissenting or devil's advocate views. Dissenting dialogue is often seen as the enemy of efficiency, but highly efficient organizations are rarely leaders in innovation; surfacing shadow conversational themes can help to enrich rather than dampen creative diversity. HRM processes in leadership development are also instrumental in building critical and integrative thinking capacity in managers, so that they are skilled at surfacing and holding open the competing views and imperatives of organizational members.

Quality of unpredictability and paradox: Managers and HR practitioners as leaders of emergent enquiry

A CRP perspective focuses attention on how unpredictability is tolerated and how paradox is a source of generative tension. An apparent paradox between two stated organizational aspirations can be an ongoing source of creative tension; e.g. Walmart's mission to be globally dominant in consumer goods *and* be a leader in environmental and social sustainability is to many a paradoxical notion, which unresolved has the potential to drive many exploratory conversations inside and outside the company. Differing, paradoxical conceptions of contestable concepts such as sustainability can be strong change motivators (Colbert and Kurucz, 2007).

Unpredictability is inseparable from creativity as emergent novelty, and therefore the focus is on processes of emergent enquiry rather than managerial operations of planning and control.

A critical role for managers then is accepting the unpredictability of the creative state, and to holding paradox open and leading enquiry on it. In the Walmart example above, the *inherent* paradoxical tension between global consumerism and environmental and social sustainability has the potential to be an overarching driver for novel meanings, innovation and change surrounding Walmart's core identity and business model. The role of the manager is to hold the paradox open and bring emergent enquiry into everyday conversation. Integrative thinking skills are relevant here, as is a capacity for triple-loop learning enquiry (Waddell, 2005). Triple-loop learning encourages us to ask fundamental questions challenging not only the rules of the game, but also the game itself, by questioning how we decide what is right. Integrative thinking allows managers to incorporate these deep questions into existing modes of operation, and to generate new meanings and innovations.

HRM processes and practitioners can lead organizationally by engaging internal and external stakeholders in surfacing and generating paradoxical creative tension. Stakeholder engagement processes (Freeman et al., 2006) and 'radical transactiveness' or engaging fringe stakeholders for competitive imagination (Hart and Sharma, 2004) can help to generate paradoxical conceptions of identity and action by drawing attention to alternate perspectives and interests regarding the organization.

CONCLUSION

Strategic human resource management has moved into the era of competitive potential, where HRM is important as a driver of strategic intent, and not only as an implementer of a predetermined course. In management scholarship, there has been a convergence of the resource-based view in strategy and SHRM, as many of the long-standing questions in the RBV are directly relevant to building competitive potential and innovative capacity. We propose that concepts inspired by complexity science, in particular the *complex responsive processes* view of organizations, can help us to understand better the innovation challenges of the RBV, and offer implications for management competencies and SHRM processes. The shifting strategic dynamics in the era of competitive potential and innovative capacity have moved particular capabilities to the fore in terms of strategic importance, and the CRP view aids in re-focusing attention on the strategically critical aspects of organization in fostering emergent novelty.

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24

Complexity and the Rise of Distributed Control in Operations Management

Arash Azadegan and Kevin J. Dooley

INTRODUCTION

Production is the creation of goods and services. Using a pool of interrelated operations, a production system generates value by transforming resources (factors and inputs) into outputs (Grubbström and Olhager, 1997; Heizer and Render, 2009). Such a system can be characterized as a collection of agents who share information, money, and physical resources with one another in order to produce goods and services of value to an external market. These agents seek to achieve common and distinct goals by communicating, making decisions, and executing decisions in response to their local environment. By definition, production systems are therefore complex adaptive systems (Dooley et al., 1995; McCarthy, 2004), regardless of their organization structure, their communication method, or their decision making approach (Dooley, 1997).

Complex systems have intrigued operations management researchers for a few decades (see McCarthy et al., 2000 for an overview). Some of the pioneering works that explored the complexity of operations in a production system were those by Jay Forrester in the 1940s, which ultimately led to the publication of the book titled *Industrial Dynamics* in 1961 (Forrester, 1961). Yet, it was not until a few decades later when interest in connecting complexity science with operations management research became more mainstream. Leonard-Barton (1988) found evidence of nonlinearity in complex production processes; Dooley and Benjaafar (1994) reported on the use of complexity-based data analysis tools to better understand manufacturing system behaviors; and Tyre and Orlikowski (1994) explored the effects of complexity on technology adoption in manufacturing and service firms. Other notable works include Pascale's (1999) review of a radical transformation at Royal Dutch Shell using principles of complexity science; and Larsen et al.'s (1999) research showing how the cascading structure of production and distribution lead to complex behaviours.

Since, complexity science has been used to explain a range of phenomena related to supply chains and logistics. For example, Choi et al. (2001: 351) highlight the emerging nature of supply networks as complex adaptive systems and suggest that, while imposing too much control may detract from innovation and flexibility, too little control may 'undermine managerial predictability' as well as the performance of organizational routines; Pathak et al. (2007) underline the relevance of complexity in supply chain and operations management research; while Bozarth et al. (2009) show how complexity upstream and downstream from a manufacturing plant can affect its competitive and customer service performance. From a logistics perspective, Nilsson and Darley (2006) show how simulating logistics and manufacturing operations as a complex adaptive system through agent-based modeling can provide better insights to managers and researchers; Li et al. (2009) show that a long term collaborative strategy among supply network partners leads to higher structural stability; while, more recently, McElvey et al. (2009) have applied complex adaptive systems concepts to explain electronic auction markets in logistics.

An important sub-topic in these research streams has been the issue of centralized versus distributed control (Pratt, 1985; Tunalv, 1990; Deshmukh et al., 1993; Lee and Billington, 1993; Mahalik and Moore, 1997). Traditionally, manufacturing organizations have controlled their operations centrally, with a small set of decision making entities in charge of a broad range of activities. More recently firms have been moving to distributed control strategies whereby control decisions about how they respond to their environment are not centralized but rather spread throughout the system. Distributed control strategies enhance flexibility and responsiveness by minimizing the distance between sensing and action, and are simpler to develop and maintain than centralized counterparts.

In this chapter we investigate the conditions which facilitate or enable a centralized control approach versus a decentralized, or distributed, control approach to managing a complex system such as that related to production. As many complexity scholars have illuminated, a centralized control approach is characteristic of mechanistic, linear systems thinking, while a distributed control approach is more compatible with complex adaptive systems thinking (Holland, 1996; Dooley, 1997; McCarthy et al., 2000). Just as scientific thought progressed over the last century from focusing on simple, mechanistic systems to complex ones, so too did the manner in which production systems were organized and controlled. A key question is thus raised: why did the shift from centralized to distributed control systems occur? To address this question, we first use an empirically grounded historical narrative to examine this shift in practice, tracing the process through which production systems have shifted from highly vertically integrated factories to vast and global networks where most work is outsourced from the product manufacturer. Second, we examine the control of manufacturing operations from the perspective of centralized versus distributed control, in terms of both production control and innovation. By examining the commonalities amongst these trends, we propose that distributed control systems are more likely to emerge in a complex supply network if there is a plurality of organizational agents with sufficient capability and opportunity to connect and interact, and there is an accompanying abundance of resources. This would suggest that the trend towards vast, global supply networks is potentially reversible, to some extent; if connectivity were to decrease significantly and resources to become scarce, production systems may revert to more centralized forms of control.

CENTRALIZED AND DISTRIBUTED CONTROL

Control drives decisions about how an organization responds to and reacts to its environment. Ideally, a controller is tasked with finding the 'optimal', or most efficient way of using limited resources to reach its objectives (Ragsdale, 2007), based on information available to it from the system. In a manufacturing network the controllers' concern is the efficient transformation of raw materials into products through a series of process steps. Here, optimal solutions minimize the costs of a given decision to members of the network while providing the most benefit. On the other hand, a quasi-optimal (Muller and Wiederhold, 2002) solution may provide the most benefit while not minimizing costs of a given decision for all members. A sub-optimal solution in contrast is one that does not provide the solution with the most benefit to the network.

One approach to decision making is to have a centralized entity. In a production system with centralized control, the authority to create and execute heuristic rules is in a single physical location (Simon, 1957; Pratt, 1985; Schilling, 2007). The central controller may be in the form of an individual (for example a CEO, Provost, or Chief Procurement Officer), a group of individuals (such as Board of Directors, Board of Regents, or corporate purchasing office), or a decision making tool (such as a central mainframe computer running corporate-wide software). The general model of such centralized control is shown in Figure 24.1. Inputs, representing observations about the current state of the system and its environment, are provided to a single system controller who makes decisions (outputs) via centralized rules that coordinate work. So long as the central controller is able to observe the entire system, decisions made by the controller can be optimal, meaning they carry the best consequences to the entire system.

However, as systems become more complex, the central controller has to reflect the complexity in its decision making, per Ashby's law of requisite variety. Ashby (1958) suggests that only by having a variety of decision choices to select from would one be able to manage the increased variety of situations that it encounters. A centralized

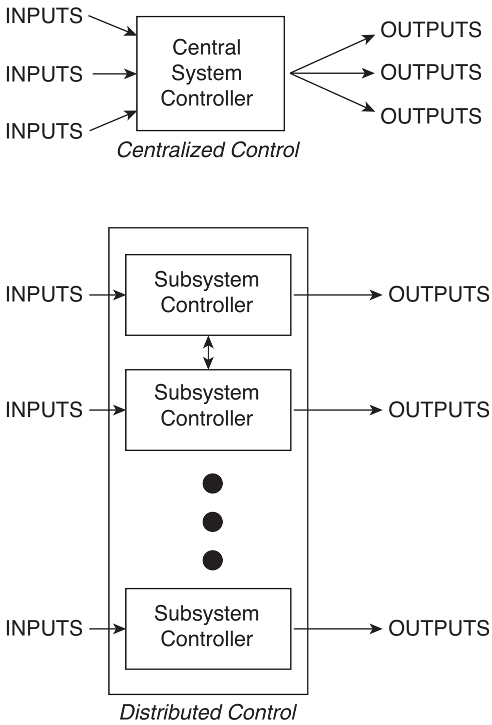

Figure 24.1 Centralized and distributed control process

controller may adapt to increased complexity by changing, and further complicating its own internal rules. With increased complexity, further changing can become ever more complicated, costly, and time-consuming. Furthermore, as systems become more complex, it may become harder to directly provide information to the central controller. With added complexity in a system, a centralized controller risks not receiving all necessary information, becoming overwhelmed by too much information, or slowing down its decision making. Barabási (2002) contrasts centralized control to a tree, where branches all lead to the same tree trunk. He notes:

> Despite its pervasiveness, there are many problems with the corporate tree … First, information must be carefully filtered as it rises in the hierarchy. If filtering is less than ideal, the overload at the top

branch can be huge. As a company expands … information at the top level inevitably explodes. (Barabási, 2002: 201)

To compensate for this loss, the centralized controller can standardize (Walker and Dooley, 1999), or tightly integrate the operations of a system (Barabási, 2002). But standardization and integration can lead to reduced flexibility. Reduced flexibility may lead to an inability to effectively respond to changes in the environment (Menon et al., 2002). In sum, as systems increase in complexity, centralized controllers typically adjust their response to ever more complexity in a system through means that minimizes their flexibility to change.

An alternative approach for production systems is through a distributed system where decision making is delegated from a single node to a multitude of agents (Tunalv, 1990; Radner, 1993). In a distributed control system a number of agents are responsible for sensing, interpreting, and controlling actions (Deshmukh et al., 1993). For example, instead of a CEO, a decentralized system can place the control in the hands of a number of business unit managers. Or instead of a large software package on a single mainframe, smaller software packages running on multiple personal computers can help make decisions.

There are three key characteristics to decentralized systems. First, because distributed control systems can be built incrementally, they tend to be easier to develop, maintain, and modify. Most parts of the system are not necessary before others are joined in. Similarly, no part of the system may be vital for it to survive. Unlike centralized systems, a distributed system continues to operate even if a node is replaced. Some suggest that these characteristics tend to lead to more stability and resilience to changes in the environment. On the other hand, agents operating in a distributed system have no central command to look towards. They decide their actions based on how they interpret their nearby surroundings.

Consider the simple example of control of automated guided vehicles (AGVs) which transport material from one production workstation to another (Yamashita, 2001). A centralized control approach would send sensor data concerning a vehicle's location and status to a central controller. The central controller would have a master list of the materials that need to be moved, and the locations and required delivery times for such movement. By analyzing the state of the system (location, status) relative to the goals (material list), the controller enacts control rules for each vehicle, acting like a central brain (Lin et al., 2006). This approach provides quasi-optimality so long as the controller's map of its environment is accurate. If the environment changes (e.g. a vehicle breaks down or a new one is added), then rules either need to be written *a priori* to cover these contingencies, or they need to be re-written when the change occurs.

A distributed control system would allow the vehicles themselves to make decisions as to where they should go, how they should get there, and which work they should pick up. By using simple rules like 'pick up the nearest material if the cart is empty' or 'stop moving if any object is within one meter' the vehicles can have embedded intelligence (Qiu et al., 2002). While any particular vehicle's actions may not be best for the whole, the system is robust to loss of vehicles, changing transportation paths, and delays. Thus, if the informational and physical states of the system cannot be well-described or do not remain relatively static – which are both more often the case than not – then a distributed control approach is more attractive than a centralized approach (Tuan and De Koster, 2006).

Figure 24.2 provides a simple outline of how centralized and decentralized systems compare in their configuration. The centralized system is heavily reliant on the central node. If the central node is removed, then the entire system fails to operate. On the other hand, the central node has full visibility of the entire system. In the decentralized system each node has less awareness of the system,

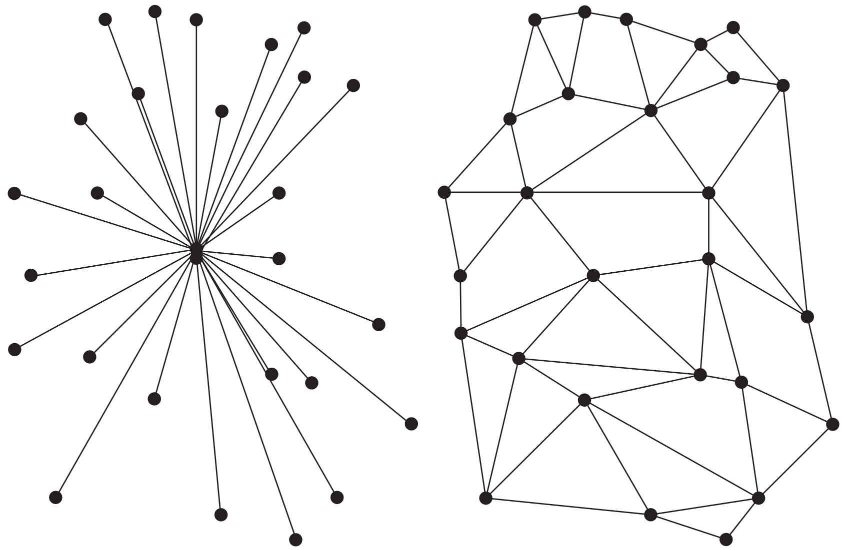

Figure 24.2 Centralized and distributed control networks

but also has a limited number of connections to maintain. If any of the nodes are removed, the system will still continue to function.

Centralized and distributed control systems may be more suited for different types of production systems. For example, a centrally scheduled manufacturing plant for commodity metals can predictably conform with demand expectations (McCaffrey et al., 1995). In contrast, a self-directed work team where control is distributed among its members can provide more flexibility and responsiveness (Levinthal and Warglien, 1999; Druskat and Wheeler, 2003). Similarly, supply chains managed through distributed control have been shown to be more responsive than centrally managed ones; while, conversely, those managed through centralized control are generally more efficient (Randall et al., 2003).

A comparative review of current production management practices to historical ones suggests a general trend away from centralized control and towards distributed control. It seems that conditions associated with centralized control are giving way to ones that lead to the rise of distributed control systems. Our goal in this chapter is to illustrate several examples of such trends to shed light on some basic conditions that facilitate the rise of centralized and distributed control approaches in order to, in turn, shed light on situations when one approach may be more appropriate than the other. Our analysis reviews the inherent characteristics of centralized and distributed control systems. We do so to identify conditions when a distributed control can be a more desirable operating system. As part of this analysis, we explain three antecedent conditions, namely abundance of resources, plurality of agents and network connectivity as necessary conditions for distributed control to become commonplace.

ORGANIZING THE FIRM: FROM VERTICAL INTEGRATION TO OUTSOURCING

Historically the production of goods has been associated with factories, which were referred to as 'manufactories' in the nineteenth and early twentieth centuries (Rigal, 2001;

Cattell et al., 2002). Manufactories were early industrial formations where large concentrations of material, human and intellectual resources were combined to leverage economies of scale towards the production of consumable goods. Low to semi-skilled workers were guided and controlled by supervisors to transform raw materials through a series of process steps.

Factories preceded roads and mass transportation, requiring them to concentrate the necessary infrastructure within centralized buildings surrounded by supporting towns or urban areas (Scott, 1988). An early example of such centrally controlled structures in manufacturing is Matthew Bolton's Soho Manufactory in Birmingham where buttons, buckles, belt locks and watch chains were assembled (Rule, 1986; Quickenden and Kover, 2007). A more prominent example of centralized manufacturing operations is Henry Ford's famous River Rouge plant. Ford used a vertically integrated chain of factories to transform iron ore into Model T automobiles in a relatively concentrated area. Through adjacencies in operation and specialization of tasks among factories, Ford was able to leverage unprecedented economies of scale from his plants (Chandler, 1964).

Economies of scale afforded by factories such as Bolton's and Ford's led to the reduction of prices for many items (e.g. automobiles, ships) and processes (building of roads, canals and general infrastructure). Shortly thereafter, new transportation and communication means (Chandler, 1990), coupled with the discovery of inexpensive sources of energy (White, 1962; Kinzer, 2003), allowed for distant operations to be interconnected. This made the need for adjacent operations unnecessary which – ironically – is argued to be the reason for Ford to give up its market dominance to General Motors a few decades later. By that time, GM had implemented a more decentralized management model (Chandler, 1964). In contrast, the tightly integrated Ford plant was unable to make even small modifications in automobile design (Davids, 1999). The Ford River Rouge plant remains a unique case of a fully centralized, vertically integrated manufactory (Pietrykowski, 1995).

Over the past century, many manufacturers have gradually shifted away from centralized operations. Much has been written justifying the benefits of decentralization through vertical disintegration (Langlois, 1990; Lorenzoni and Lipparini, 1999; Chen, 2005; Jacobides, 2005). By relying on others' operations, be they alternative sites, divisions, suppliers or nations, organizations have become more specialized and therefore beneficiaries of further economies of scale (Prahalad and Hamel, 1990; Burt et al., 2003). But without adequate road and transportation systems, sourcing from others was impossible (Winder, 1999). Moreover, a readily available pool of skilled and talented workers across the globe was helpful as firms began to break apart and relocate to multiple locations. The major shift in workforce abundance occurred just after the end of the Second World War where a shortage of skilled workers gave way to an abundance of human resources. At the same time, the combination of product variety and customization justified the need for increased production, consumption and thereby growth. As a result of these changes, vertically integrated operations became broken up and hence less common (Christensen et al., 2002).

The trend today is towards even more vertical disintegration. Reduced trade barriers and globalization have helped add new markets, and new sources of raw materials which have further extended the breadth and reach of the supply chain (Gottfredson et al., 2005). Advancements in technological, communication and managerial techniques have allowed for many of the value added steps in the 'supply chain' of producing goods to be done away from a central location. As a result, some of the central paradigms of operations and supply chain management (e.g. MRP, ERP and full automation) which were based on the structural needs of a centralized system are being reconsidered (Kumar and Hillegersberg, 2000; Rondeau and Litteral, 2001). To fit the challenges of a decentralized, interconnected supply network (Choi et al., 2001), these and other manufacturing/supply chain tools may need a fresh redesign.

How can we explain this shift from vertical integration to outsourcing? Ashby (1958) would suggest that as the pace of environmental change increases, organizational speed of response becomes essential. While centralized control systems often fall behind, through increased specialization and interdependence, decentralized control may manage more effectively in these contexts. However, the centralized approach attempts to leverage economies of scale by placing the process steps near one another, both in terms of physical proximity and in terms of managerial decision making. The vertically integrated approach assumes that tapping into distant sources is either geographically infeasible or managerially difficult to administer. On the other hand, the distributed approach is less concerned with geography or decision making issues. Instead, it leverages competitive markets for sourcing its material and distributed agents for its decision making. Underlying the functionality of a decentralized system is that the broader market provides more choices, which allow for more trials and eventually efficient forms of production.

Based on the above, it would appear that the centralized approach may be a suitable means of control in networks so long as there is limited availability of human and capital resources in the landscape. When the broader landscape remains inferior to the immediate surroundings, centralized control seems to flourish. In contrast, conditions for distributed manufacturing run parallel to having adequate human and capital resources throughout the landscape and with having necessary physical and informational connections among. We explore these infrastructure and resource limitation issues as related to plant production systems next.

ORGANIZING PRODUCTION: FROM MASS TO LEAN PRODUCTION

The original Ford production lines were built for efficiency of the production process itself. The paced assembly line relegated equal work loads across a sequential production process so that entire automobiles could be produced at an equal pace. Although the success of the assembly line made cars more affordable, the advent of more customers meant more variation in market demand. Some manufacturers responded by adjusting their production capacity to demand, so that over- and under-production was curtailed. The long cycle time required for building a car implied that parts and labor quantities had to be chosen independent of the actual demand, i.e. production was planned, or 'pushed'. Market forecasts were used to determine a monthly production requirement which was then translated into an hourly production rate. This constant production rate had a positive side benefit – by minimizing the variability of the production rate, upstream supply chain processes and downstream distribution processes could also be synchronized, leading to further efficiencies. For example, having certainty of the day's total production allowed the automobile maker to order the right amount of steel for its automobile bodies, and allowed them to schedule trains to transport production to local retailers across the country. This model became the norm across the industry.

As noted in the previous section, decisions within these systems were highly centralized. In the case of the automotive production system, demand was predicted by corporate marketing, auto designs came from corporate engineering, and production processes were developed by corporate manufacturing. Individual production plants were physically distant from one another, making the actual manufacturing task less centralized. Nevertheless, within each plant execution authority was highly centralized. Only a handful of managers typically decided on what equipment to buy, who to hire, and how to execute the manufacturing task.

Ford was in essence, the automobile company that led the way toward the era of 'build to plan'. It was another automobile company that led the way away from it. Toyota is recognized by most as being largely responsible for a revolutionary change in how production systems were managed, starting in the 1980s (Womack and Roos, 1990; Spear and Bowen, 1999). A key premise of the Toyota Production System is that waste of all sorts should be eliminated from the production process (Liker and Morgan, 2006). Waste includes that of building too few or too many products because production can only react to planned demand rather than actual demand (Pegels, 1984). In order to match production to demand, the time to build a car had to be reduced. Furthermore, the system had to both adapt to changing demand as well as maintain resilience to system disturbances (Coleman and Vaghefi, 1994; Vaghefi et al., 2000). To accommodate these needs, Toyota implemented a decentralized approach, better known as the 'pull system' (Black, 2007). In the pull system, consumer demand is used to authorize work from the most immediate upstream process, which in turn triggers other upstream processes to engage work (Krafcik, 1988). This 'build to demand' process ensures that work is executed only when it is needed (Gunasekaran and Ngai, 2005).

There are fundamental distinctions between the 'push' and the 'pull' system. The authorization of work in a push system is centralized, residing in a production planning group and a set of standardized and static work instructions. The work that is performed is the work that is centrally planned. In a pull system, work is authorized by the next downstream subsystem; similarly, decisions concerning how to execute the work are left to the actual worker, which minimizes decision making delay and builds up local intelligence, leading to further improvements and efficiencies (Spearman and Zazanis, 1992). In a push system, efficiency is measured by productivity, namely how efficiently inputs are converted to outputs. In a pull system, efficiency is measured by how closely supply meets demand (Pyke and Cohen, 1990). The central controller in a push system sees asset utilization as its main goal; the distributed controllers in a pull system see matching supply to demand as their collective main goal. In sum, a push system aims for global optimization, at the expense of local waste. A pull system allows for local optimization to minimize such waste. However, pull systems cannot always be implemented as they require a set of precedent conditions, as evidenced by the Toyota example.

Some factors helped with the rise of pull systems. First, for decisions to be made locally rather than globally, workers had the skills to sense and solve problems themselves, without involvement by corporate-level actors. Toyota achieved this by emphasizing training, problem solving skills, and increasing decision-making authority (Towill, 1996). Hamel denotes: 'Unlike its Western rivals, Toyota has long believed that first-line employees can be more than cogs in a soulless manufacturing machine. … Toyota gave every employee the skills, tools and the permission to solve problems' (Hamel, 2006: 74).

Second, information about market demand was shared across the network as quickly as possible. Toyota (and others such as Hyundai) managed to capture market demand in real-time and implemented information systems that allowed them to be reacted to in real-time (Lee and Jo, 2007). Furthermore, demand information had to be connected to all of the constituent processes in the value chain. In Toyota's case, they invented an approach called 'Kanban' (Cheser, 1994) which uses simply physical cards in order to coordinate work and information between two adjacent work activities.

Lastly, there was assurance of availability of resources (material and human) for Toyota to leverage. The company ensured there was an abundance of raw material and human resources by implementing long term commitments to their suppliers and to their employees (Liker and Choi, 2004). Each of these factors helped ensure that a distributed control mechanism could be implemented and maintained at Toyota.

ORGANIZING INNOVATION: FROM PLANNED AND PROPRIETARY INNOVATION TO ITERATIVE AND OPEN INNOVATION

For the majority of the twentieth century, companies were prone to developing ideas in close quarters, and in keeping them central to their locus of control (Nelson and Quick, 2006). The scarcity of external knowledge forced large organizations, such as AT&T, Siemens, and Kodak, to invest heavily in their centralized research and development. The decades following the Second World War were the golden age of corporate R&D departments where product development in large centralized laboratories, such as that of IBM, was the norm. This 'closed' world of innovation was based on a logic of deep vertical integration and the monopolization of knowledge within one's immediate corporate control (Chesbrough, 2006).

The world of research and development has since changed. These days the 'silo' approach to research and development is being challenged by more distributed alternatives. R&D traditionalists are being bypassed by a new breed of organizations, the likes of Nokia and Genentech (Chesbrough, 2006). Cisco, another example of a firm with an open innovation framework, has leveraged outside innovation through acquisition, joint ventures and startup funding. The newcomers' mode of operation incorporates explorations for novel practices that are scattered beyond the immediacy of a centralized control unit or individual. The belief is that in any domain of activity, much useable knowledge will reside within the broader environment.

During the past few decades the innovation landscape has been redrawn. In the past a barren landscape of innovation forced organizations to control innovations near their proverbial organizational 'chest'. Today most organizations are surrounded by a rich landscape of relevant knowledge. As a result, an equally important task to developing knowledge is to identify, access, and integrate what is applicable from this large pool. The open innovation model's essence is the harnessing and combining of available innovations regardless of their source.

What has been the underlying cause of such shift from centralized innovation programs to the leveraging of broader sources of ideas in an open system? An innovator's main concern is the efficient transformation of novel ideas into new products that meet unmet needs of the consumer. The centralized approach attempts to allow for this transformation by placing the necessary brainpower and infrastructure in proximate confines of centralized control. The centralized approach considers that what is collected and developed within the purview of centralized control to be better than what resides away from it. On the other hand, the distributed approach to innovation does not limit search to within the confines of centralized control. It involves tapping into the broader world to see where novel ideas are as well as whether and how they can be combined. Incorporating these 'partially connected agents' (McCarthy et al., 2006: 452) enhances an organization's adaptability to innovation needs.

The shift from closed to open innovation systems appears to have coincided with some key changes in the innovation landscape. First, increased mobility of professionals and transfer of knowledge has made it more difficult for traditional R&D organizations to control ideas (Florida, 2002; Chesbrough, 2003). When professionals left their jobs, they took years of training and skills with them. Second, there are now more trained professionals in most fields. Higher education became more accessible after the 1950s, adding a yearly pool of fresh talent to the already established set of professionals.

Third, availability of additional venture capital meant that good ideas that may have been rejected by one organization may be picked up by another, perhaps a startup. These three factors, alongside the ease of communication due to new technologies, made for faster development and implementation of innovations.

The distributed approach assumes that no matter how elaborate and effective centrally controlled research and development capabilities may be, there are novel ideas beyond them that are worth considering. So long as there are limitations to the availability of knowledge across one's landscape, the centralized approach is more suited. In fact, despite the appeal of open innovation systems, in some industries innovation is still centrally controlled by a small group of large organizations, such as jet engines and nuclear power plants (Joppke, 1992).

Not only have changes occurred in where innovative ideas come from, but also in how they are developed into tangible designs. Traditionally, innovation has been conceptualized as a work process similar to a production process. While the tasks may have more uncertainty and unexpected activities like product redesigns are inherent elements of the design process, the assumption is that the new product development process is best executed by knowing as best possible which work needs to be done, who is going to do it, and how it is going to be done. This 'project management' approach requires that a development team identify requirements, link design activities to requirements, and execute. After requirements are made, a conceptual design is developed, and then detailed design of system and subsystem component ensues, with necessary integration steps.

Control of the innovation process when using such a centralized approach resides in the firm's engineering department, and development teams tend to be made up of only engineers; manufacturing and marketing expertise may be sought, but only as inputs and outputs to the core, functional decision making. Design work is assumed to take place in a strictly linear fashion: a conceptual design is developed only after understanding the market; a detailed design is developed only after a concept is chosen; and a production plan is only determined once the detailed design is complete. Desires to reduce the cycle time associated with these activities may force the firm to overlap activities, beginning a downstream activity before an upstream one is complete, but the workflow assumptions are still the same. In software engineering, this design process became known as the 'waterfall' model, because it was easy to swim downstream but hard to swim upstream to 'redo' an earlier activity. Thus, if customer requirements changed significantly, a new concept might have to be developed, thus wasting all the activity up to that point. Likewise, when dealing with risky innovations, viability might not be demonstrable until significant detailed design has occurred, invoking yet more risk of wasted activity.

Automobile and other consumer companies were among the first to move towards a more distributed model of design decision making (Denison et al., 1996). Recognizing that there were advantages to having a tight fit between the customer, the design, and its corresponding manufacturing process, cross-functional design teams began to be implemented. Rather than consult with procurement or manufacturing or marketing experts, designers worked hand-in-hand with these other functional areas as part of the same team (Donnelon, 1995).

The field of software engineering, dealing with the development of new software products, has recently moved to more decentralized, distributed models of controlling the innovation process itself. There was recognition that not all requirements can be known completely before design begins, and not all required activities can be identified. Whereas a linear sequence of design work assumes that project planning, requirements analysis, and conceptual design are activities to be performed once, an iterative approach to design assumes that planning occurs constantly, and requirements often have to be identified using multiple, conceptual prototypes. Many studies have shown an iterative approach to be superior in situations where requirements and/or technology capabilities have a significant amount of uncertainty (Eisenhardt and Tabrizi, 1995; Terwiesch et al., 2002; Lin et al., 2008).

What enabled innovation to be managed in a more distributed, iterative manner? Ashby's law of requisite variety implies the need for increased decision choices in order to meet the increased variation in the environment. Without multiple ideas there is no opportunity to invoke multiple conceptual designs so the innovation process can benefit from having access to an abundance of ideas. As discussed earlier in this section, it is preferable to have openness to the source of the ideas, whether they arise internally in a department outside of design or externally via a customer or supplier. Second, in order for design decisions to be distributed, there has to be an abundance of competent and creative designers. Part of this was driven by the large increase in the number of engineering graduates starting in the 1960s and peaking in the 1980s. Part was also due to the influx of computer-aided design tools that allowed significant efficiency gains through electronic transfer of design information, part design databases, re-use, analytical modeling, and rapid prototyping. Third, information technology facilitated collaboration between physically separated parties, whether in the form of cross-functional and/or interfirm collaboration, or even in interactions with the customer.

DISCUSSION – CENTRALIZED AND DISTRIBUTED CONTROL – A SIDE BY SIDE APPRAISAL

Our examples of the general progression in industrial behavior suggest some fundamental differences between centralized and distributed control. Centrally controlled systems allow for tight coordination of efforts, with a central command unit deciding on the allocation of tasks and resources. Centralized control also ensures that communication between agents is routed through and filtered by this central command unit in order to further enhance the efficiency of the system by making sure that agents are not preoccupied by responding to communication that is not relevant to their immediate task. In sum, a centralized system is superior at making the best of a situation with limitations on resources and connectivity, and in finding optimalities within a less complex system.

However, as noted in our examples, the advantages of a centralized control system seem to diminish once limitations on resources and connectivity are removed and as systems become more complex. Centralized control systems seem to have become less effective once more infrastructure was introduced into the automotive arena of the early twentieth century. Centralized control was of less use to Toyota which used better communication methods to incorporate real time demand data into its production operations. Lastly, centralized control seems to become a less effective approach to R&D than more open forms when a plurality of capable agents populates the innovation landscape. Alongside the rise of infrastructure, better communication and plurality of capable agents, more complexity was introduced into these systems. It seems therefore, that the rise of the three phenomena accompanies the rise of distributed control systems.

Some key characteristics distinguish distributed control systems from centralized ones (see Table 24.1). First, in terms of decision pursuit, distributed systems are inherently sub-optimal (i.e. considering the benefits of the entire system is more difficult) as they are built using trials and errors. Optimality requires deciding on clear and distinctive goals based on facts and specifics, in situations where bounded instability (Stacey, 1995) provides assurance of a linear relationship between input and output, or effort and outcome. In contrast, distributed

Table 24.1 Comparison of centralized and distributed control

	Centralized control	*Distributed control*	*Conditions*
Landscape	Suited for predictable landscapes with bounded instability	Suited for unpredictable instability, constant and varying change	Resource Abundance
Decision pursuit	Allows specialization on one path	Allows pursuing potentially conflicting paths	
	Fit for dealing with known uncertainties	Fit for dealing with unknown uncertainties	
	Quicker strategic decisions	Quicker local decisions	
Decision measurement	Economies of Scale on Decision-making	Economies of Scale on pre-specified operations	Network Connectivity
	Controllable trial rate	High failure rate – or uncontrollable trial rate	
	Milestone based progress, planning and analysis	Non-deterministic progress	
	Linear relations between input and output, effort and reward	Non-linear relations between input and output.	
Agents	Responsibility is: Chosen for (i.e. delegated) –Through matching task with system needs	Responsibility is: Chosen by (i.e. self-selected) –Through matching task with skills	Plural Agents
	Motivation – Need for tangible compensation • Salary, bonus, etc. – More duty than zeal	Motivation – Need for intangible compensation • Reputation, awards, identity. – More zeal than duty	
	Appropriation decisions are easier to manage	Appropriation is an issue	

control decisions are set to be more reliable and stable such that they can survive changes and modifications to the business environment. In a land of abundance, there is less need for emphasis on conservation or efficiency in use of resources. However, through concurrent processing (Maturana et al., 2005), distributed controls can pursue a multitude of alternative solutions simultaneously, even if some may seem contradictory or conflicting; concurrent processing allows multiple solutions to be maintained while the system adapts to new environmental conditions (Holland, 1996). Distributed control systems trade off optimality with more resilience and reliability by using heuristic rules developed through common consensus.

Although distributed control systems may be inherently sensitive to small changes in their environment, they respond to larger changes by allowing new patterns of coordination to emerge among many agents. This makes system-level strategic decision making more difficult in distributed control. In turn, allowing agents to react to their immediate surroundings enhances local decision making. In addition, there may be no direct correlation between input and output, or effort and reward under such a control. As a result, determining the productivity of distributed control systems is inherently difficult. Without a central command, agents in the distributed system may specialize in the same activities, i.e. develop redundant skills, which may reduce the potential performance of the system. However, this allows for decentralized control to rely on these overlapping familiarities to develop better heuristics.

Lastly, the role and motivation of agents in distributed control is distinct from that of centralized ones. Whereas responsibility in centralized control is delegated, agents in distributed control systems have more freedom to choose their role. There is inherent choice and freedom for the agents to specialize and diversify in a distributed control system (Lakhani and Panetta, 2007). This makes distributed systems better suited to situations where tasks and responsibilities are open ended and less deterministic. In centralized control settings, having common goals, requirements for completion of tasks and clear milestones are what motivate members (Wenger and Snyder, 2000). In contrast, for those in a distributed system proper alignment of task with skills, and self-reputation of the agent are better motivators.

All this points to distributed systems being better suited for landscapes where a stable equilibrium in the environment is uncommon (i.e. where there is constant change in the environment) and when there is adequate time to adapt to any major changes; decentralized control appears to be better suited for situations where trials and failures are tolerated. For example, open source software allows for codes to be written and rewritten by many. Wikipedia allows for anyone to post material, recognizing that reported errors will likely be corrected by others. In contrast, design of nuclear power plants or large aircraft engine do not provide the possibility for error corrections. Distributed controls provide freedom for participants to choose their skill, specialization and pace of work. The tradeoff here is that project progress is difficult to reliably determine. As such, projects where tight deadlines, tight resource requirements or tight quality are required may not be suited for distributed control. Table 24.1 summarizes our comparison of centralized and distributed control and how they relate to the three enabling conditions discussed in this chapter.

IMPLICATIONS – THE RISE OF DISTRIBUTED CONTROL AND COMPLEXITY

A fire is a simple example of a self-organizing, self-sustaining, adaptive system. Students of fire prevention, from Boy Scouts to emergency rescue teams and wild fire fighters are familiar with the 'fire triangle' (Gil, 2008). This simple model suggests that in order to ignite and continue to burn, a fire requires three elements, namely oxygen, heat and fuel. Removing any of the three elements leads to the elimination of the fire. Using high volumes of water through fire sprinklers drops the temperature, while using fire extinguishers bans oxygen from entering the system. Burning a perimeter area around the fire, a common approach for managing forest fires, allows for depleting the available fuel. In sum, a fire and all the complexities associated with it, is dependent on the interaction of several factors.

Our discussions in this chapter suggest that a similar model to that of the Fire Triangle can portray the rise and sustenance of distributed control systems. In each of our examples, three underlying conditions were coincidental with the onset of distributed control strategies. First, there was a population of agents in the environment. Without a large pool of agents, trial and error and iterative learning seemed to be less apparent than when distributed control surfaced. Second, an abundant landscape with useful resources seemed to coincide with the rise of distributed control. What made open innovation in industrial settings less possible prior to the 1990s was the lack of a profusion of information. Similarly, lack of abundant energy before the discovery of fossil fuels made transportation and therefore interconnected manufacturing impractical until the turn of the nineteenth century. The third element that coincides with the rise of distributed control is that of open communication between agents, i.e. network connectivity. Prior to the advent of the internet this was practically impossible, which made open source software practices and perhaps the advent of open innovation impossible. Henry Ford had to centralize because there was inadequate infrastructure to support his needs (Langlois, 1990).

Our discussions in this chapter explored how manufacturing systems have shifted from centralized to decentralized systems in order to better respond to changes in their environment. We witnessed how the increased availability of alternative sources of raw materials and infrastructure have allowed for more manufacturing, design and supply capabilities to flourish throughout the globe. Furthermore, the availability of better material for training (i.e. information technology and communication) allows for better education and skills development, leading to more capable agents. Simultaneously, enhanced infrastructure in terms of roads and information technology has allowed for better connectivity among the agents. We explained these changes based on Ashby's law of requisite variety. The combination of these three facts (abundance, plural intelligent agents, and freedom of communication) is necessary (Figure 24.3). Arguably the interaction between these factors, which may lead to increased complexity of the environment, seems to be better managed through a decentralized form of control. It is therefore plausible to consider the rise of distributed control to be associated with a rise in complexity of systems. As such, close observation and thorough understanding of the characteristics associated with decentralized control systems may be beneficial in understanding the dynamics associated with complexity.

There are a number of ways in which our model could be empirically tested. An agent-based model could be developed that simulated either the open innovation or distributed manufacturing control contexts, and secondary data could be used to parameterize and calibrate the model. For example, one could examine how increasing uncertainty coupled with vertical disintegration (plurality of agents), increased competition (resource abundance), and the availability of information technology (network connectivity) led to the increased preferability of lean practices. Similarly, secondary data on these practices and econometric variables could be collected

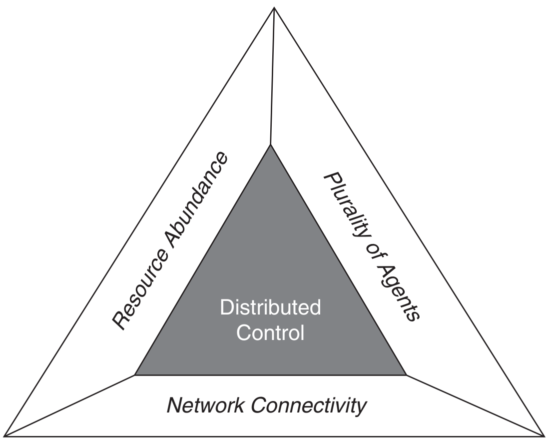

Figure 24.3 The distributed control triangle

and modeled using time series to determine if there is the presence of correlation over time.

In general the movement towards distributed control is one that is happening in each area of the organization where there are control issues – e.g. logistics, supply chain coordination, production scheduling, innovation, project management, software development, etc. As we have shown here in this chapter, there is benefit to stepping back and viewing these shifts from a broader perspective, as they represent a somewhat silent but wholesale shift in the basic way that we organize human economic activity.

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25

Knowledge Management and Complexity

Max Boisot

INTRODUCTION: MAKING SENSE OF A COMPLEX WORLD

As intelligent beings, we act, survive and prosper on the basis of knowledge that we deploy as an adaptive response to the diversity of phenomena we encounter and have to adapt to (see Boisot and McKelvey, this volume). Effective action, however, requires us to make sense of and relate to a world that is becoming ever more connected, and, by implication, ever more complex. Today, what may appear to be a strictly local interaction between feuding tribesmen in the mountains of Waziristan, within hours can affect the share price of utilities on Hong Kong's Hang Seng Index. But given our inability to interpret the meaning of long and complex causal chains in a timely manner, the link between the two events typically only becomes apparent to us *ex post*. Closer to home, the recent sub-prime mortgage crisis furnishes us with another example of complex local interactions whose effects spread globally in unforeseeable ways. Yet policy makers in government and business are increasingly-expected to anticipate and respond adaptively *ex ante* to this kind of complexity. Is this a reasonable expectation? And as policy makers attempt to respond, does it help that they now live in a so-called 'knowledge economy'? Does the availability of new information and communication technologies (ICTs), of the Internet, of text messaging, of vast data bases, etc., effectively add to the knowledge that we need to deal with increasing complexity? or could it be that it merely adds to that complexity?

Information theory teaches us that complex phenomena are higher in information content than simple ones (Shannon, 1948). If we take complexity to be a function both of the number of elements in interaction in a system (Mitchell, 2009) as well as of the nonlinearity of these interactions, then we can say that a complex system has the capacity to generate a larger number of internal states in response to the variety of the external world than a simple one and that many of these states will require more data for their description. Thus the total data required to describe the system will be a function of the total number of elements and links activated by each distinguishable state multiplied by the number of these states. Not all of the data will be information bearing, however. If, following Bateson (1979), we take information to be 'the difference that makes a difference', then only those states that make a difference will be information bearing. And since making a difference means making a difference to some information processing agent, whether animate or inanimate, it is clear that what is taken to be information-bearing will vary from agent to agent, reflecting the variety of intentions and expectations that characterize agents as a group. In the human case, intentions and expectations are shaped by a given agent's background knowledge and experiences, by the agent's feelings, and by her ethical stance. These help to identify those states that are relevant for a given purpose and to discard the rest as noise. In this way, data that is non-information-bearing is ignored, allowing the agent to husband her scarce data processing and storage resources. A radiology student, for example, has to process more data to interpret an X-ray picture than an expert in the field whose years of experience allow him to discard massive amounts of data at a glance.

The larger the number of states that are deemed relevant to an agent and to which it can respond adaptively, the greater the agent's capacity for handling complexity and the more wide-ranging his expertise. Here, however, we must distinguish between complexity as an objectively given property of a situation or phenomenon and complexity as subjectively experienced by the agent. Viewed objectively, more knowledge can handle greater complexity. In a communicative context, Shannon (1948) took information to be that which reduced the uncertainty – i.e. the entropy – of the receiver with respect to the information content of the message. Yet the greater the background knowledge of the receiver – familiarity with the context that conditions her prior expectations – the less likely she is to be surprised by incoming data. For her, such data will then be less information-bearing than it would be for a less knowledgeable agent. Viewed subjectively, then, complexity is experienced as those states that the agent's existing knowledge cannot handle. In both the objective and subjective cases, complexity sets a limit to what we can effectively know, but in the subjective case, knowledge and complexity are inversely related. Limits to knowledge, however, are more problematic for some conceptions of it than for others. A strictly Platonic view of knowledge as justified true belief, for example, is challenged by Kurt Gödel's demonstration in 1931 that we can only ever justify a small subset of what is true (Gödel, 1931). A more pragmatic view of knowledge as a practical aid to biological survival, one that is either enhanced or impeded by our affective and ethical stance, is less threatened by our epistemic limits.

The foregoing suggests that our ability to grow and manage our knowledge base will determine how much complexity we can handle. Knowledge management and complexity thus need to dialogue. We explore the scope for such a dialogue in this chapter. In the first section, we discuss the challenges of complexity. In the second section, we then describe knowledge management and offer a critique. In the third section we present a conceptual framework that brings them together and in the fourth section we assess the role played by the new ICTs. In the concluding section, we look at the challenges and opportunities for knowledge management in an increasingly complex world.

THE CHALLENGE OF COMPLEXITY

As yet, there is no single and unified complexity science (Mitchell, 2009). But, the increasing power of information and communication technologies has given us access to a number of powerful concepts in the past decades that are collectively labelled the sciences of complexity. The term 'complexity', however, does not resonate in the same way in the natural and in the social sciences. In the first, meaning and interpretation are the business of independent observers located outside the system under study. They cannot therefore, *qua* observers, affect the complexity of the system.[1] In the second, observers form part of the system and through their interactions with it, actively contribute to the system's complexity. Meaning and interpretation are therefore endogenized – think, for example, of how the behaviour of rioter or movie stars can be modified by the mere presence of TV cameras. In the case of the natural sciences, the knowledge one gains is deemed to be 'objective' (Popper, 1972); in the case of the social sciences it is also freighted with subjectivity. The evolution of both kinds of knowledge will be affected by the interplay of interests, power, feelings and ethical constraints within the community of observers, whether these are external or internal to the system. If, in the natural sciences, the challenge is to acquire knowledge of systems consisting of a large number of parts interacting in nonlinear ways, in the social sciences one is also trying to acquire knowledge of agents whose nonlinear interactions are partly guided by the different ways that they represent the system both to themselves and to each other. Their interactions are conditioned as much by the flow of information as by the action of physical forces.

The new sciences of complexity appear on the scene at a time when the ever-increasing connectivity of an ever-increasing number of actors and nonlinear processes in the world that we live in – the signature of globalization at work – points to the unprecedented levels of complexity that we are now required to adapt to. Unfortunately, as we have just seen, that same complexity sets practical (if not necessarily theoretical) limits to the knowledge that we can acquire to deal with it. A common response to this problem has been to collect more data. But not all data is information-bearing and not all information will yield knowledge. As the Enron scandal demonstrated, being flooded with too much meaningless data can end up reducing our access to knowledge if we lack the means of processing it in a timely manner so as to extract the relevant information from it. We then experience the data as *random noise*.

Such limitations apply primarily to *knowledge-as-prediction* where prediction typically requires a detailed and explicit representation of key features of phenomena as well as of how these relate to each other. *Knowledge-as-understanding*, by contrast, may require no more than a feeling for significant if fuzzy patterns that, when recognized, give rise to anticipation without necessarily leading to prediction. Anticipation rather than prediction, for example, is what scenario planning delivered to Shell in the mid 1970s allowing it to speedily recognize a pattern that it had already processed some time before and to be the first to adapt to the oil crisis. Its pattern-recognition skills thus secured a durable first-mover advantage for the firm while its competitors were floundering, trying to make sense of the situation (Wack, 1985a, b).

Some, aligning themselves with Lord Kelvin, would say that unless you can measure precisely and predict, you haven't yet got knowledge. This is close to the platonic view of knowledge in which prediction justifies belief. It is held by many natural scientists and in many instances – the case, for example, of particle physics – it delivers. Yet complexity does not allow much in the way of prediction. Indeed, under certain circumstances, complexity gives rise to emergent phenomena – hurricanes, earthquakes, stock market crashes, etc. – that defy any form of prediction (Holland, 1975; Bak, 1996). It remains an open question how far these can be anticipated or even articulated. We are thus moving ever further away from the linear and mechanistic world of Pierre Simon de Laplace who claimed that with a complete and precise knowledge of the state of the world at time t_1 he could predict its state at time t_2.

But what, then, of knowledge as understanding? How does it relate to prediction and, by implication, to measurement? Do predictability and understanding constitute alternative ways of seeing the world? Or does the realization of the one facilitate the realization of the other? Operationalism saw predictability as gradually leading to understanding (Bridgeman, 1927). Others see understanding as ultimately leading to prediction.

Both aim to align subjective and objective states. Is the aim realistic? How far should we take complexity and knowledge as being antithetical to each other?

Can we even measure complexity? If we could, we may at least claim to have knowledge of it in Lord Kelvin's terms. Chaitin, (1974) and Kolmogorov, (1965) take the complexity of a phenomenon to be measured by the length of the shortest computer program that would reproduce it. Chaitin calls this measure the *algorithmic information complexity* (AIC) of the phenomenon. Gell-Mann, however, agues that AIC measures the entropy of the system – its degree of disorder – and thus fails to distinguish between complexity and randomness (Gell-Mann, 2002). He distinguishes between *crude* and *effective* complexity. Crude complexity is measured by AIC whereas effective complexity is measured by the shortest programme that can reproduce, not the phenomenon itself, but the *regularities* that reside within it – i.e., its degree of structure or organization. Yet, as implied by our discussion above, we may never get to know what effectively constitutes the shortest programme. To someone applying model A, for example, the phenomenon will be experienced as simple, whereas to someone applying model B it will be experienced as hopelessly complex. Indeed, the difference between models A and B – pointing to the enduringly subjective dimension of model choice – is the basis of all encryption technologies.

As we saw, we inherit from Plato a conception of knowledge that binds it to certainty and truth. Predictability is deemed to get you closer to both. However, as Plato himself pointed out, we live in an imperfect world where certainty and truth are not generally on offer. Some, therefore, take valid knowledge to be whatever permits you to act in adaptive ways given the complexity you confront, This is the pragmatic view of knowledge that we associate with Charles Sanders Peirce and William James (Peirce, 1931–1958; James, 2000) The more knowledge you have, and the better you make use of it, the greater your chances of adapting, surviving and prospering. This way of thinking powered the rise of Baconian science. Recently it has spread beyond science to shape the orientation towards knowledge in general of commercial and other types of organization. It has given rise to a new practice: knowledge management. We turn to this next.

KNOWLEDGE MANAGEMENT AS A RESPONSE TO COMPLEXITY

Mankind has always recognized the value of knowledge but has had difficulty defining and managing it. In ancient times, it was the preserve either of a priesthood or a small literate elite. Following Gutenberg's development of the printing press in 1440 and the resulting spread of literacy, access to knowledge in Europe gradually became democratized.[2] Arguably, the first institutionalized attempt to systematically manage the creation, dissemination and employment of knowledge was the creation of the Royal Society in Britain in 1660, followed a few years later by the creation of the *Académie des Sciences* in France. By the eighteenth century, Europe's scientific academies had effectively created the world's first knowledge management organizations. Yet, although today many claim knowledge management to be an intellectual discipline in its own right with university courses offered in the subject and professional and academic journals devoted to the topic, there is, as yet, no unanimously agreed upon definition of knowledge management or any clear understanding of what, exactly, it covers. Much of the interest in the subject has been driven by the technological possibilities offered by the new ICTs – i.e. the Internet and mobile telephony. A Wikipedia article on knowledge management frames it as either a *techno-economic*, an *organizational*, or an *ecological* phenomenon.

The *techno-economic* perspective treats knowledge as an economically valuable intangible asset that forms part of an organization's intellectual capital (Edvinsson and Malone, 1997; Stewart, 1997; Sveiby, 1997). To properly exploit the asset it has to be measured (Hand and Lev, 2003) and for some that means that it first has to be articulated (Davenport and Prusak, 1988; Nonaka and Takeuchi, 1994; Von Krogh, 1995; Probst and Davenport, 2002). Knowledge articulation then allows the new ICTs to capture, store, and retrieve knowledge allowing it to be rapidly shared within and across organizations. How far knowledge has to be articulated in order to be exploitable is a matter of debate (David, 1987; Foray and Steinmueller, 2003). Those who follow Polanyi (1958) point to the tacit residue of uncodified knowledge that dogs all attempts at a complete articulation. Some will take the tacit knowledge embodied in routines and other behavioural regularities as their point of reference (Nelson and Winter, 1982); others will accept the articulation of knowledge into a narrative form but resist the distortions entailed by formalizing it further into purely abstract-symbolic representations (Snowden undated). These different types of knowledge – embodied, narrative, and abstract symbolic – can all be embedded in artifacts.

The *organizational* perspective would treat knowledge as a basis for the kind of intelligent coordinated action that characterizes agency. A group of individuals exhibit organized agency when they can coordinate their actions in pursuit of some collectively agreed upon goal. For this to happen they need to achieve a capacity for collective sense making (Weick, 1993; Spender, 1996). It does not happen spontaneously and requires organizational learning (March, 1991). Although organized agency is formalized in the concept of the firm, a bounded entity endowed with a legal personality, the growth of communities of practice suggest that it requires neither boundaries nor a legal personality to function (Lave and Wenger, 1991; Brown and Duguid, 2000). Yet a more networked view of agency raises the issue of complexity. Can the different agents that make up complex interactive networks agree upon goals with sufficient clarity to allow collective agency to emerge and function?

At the extreme, the organizational perspective yields to the *ecological* one. Here, knowledge comes into being through complex networks of social interaction, and then either dissipates or gets internalized to guide the action of individuals or groups (Borgatti and Everett, 1999). Whereas some of these interactive networks will look like cohesive organizations such as firms, others will be more loosely coupled and could look more like markets or other types of community (Boisot and Lu, 2007). Such loose coupling underpins a *distributed* model of the knowledge management process, one more aligned with Friedrich Hayek's (1945) conception of how society effectively uses knowledge (Jelinek and Schoonhoven, 1994). Interactive scalable networks generate and disseminate new knowledge through a bottom-up emergent process that Prietula and others have likened to a socio-computational process (Prietula, et al., 1998; Tsoukas, 2005). Interactive scalable networks introduce complexity thinking into knowledge management. Effective participation in such networks builds up the social capital of agents who then become attractive nodes within them (Coleman, 1990; Burt, 1992; Nahapiet and Goshal, 1998; Burt, 2005), the size of the network being limited only by its computational capacity and the requirements of collective agency (Buchanan and Tullock, 1962).

We can place these three perspectives on knowledge along a continuum. At one end knowledge is converted into an object that can be manipulated, combined with or embedded in other objects – both physical and virtual – stored, retrieved and transmitted. Such an object becomes a knowledge asset when it yields a stream of services over time. Intellectual capital is accumulated by building up a stock of these knowledge assets. At this end of the continuum the main concern of knowledge management is getting an organization to make good use of its knowledge assets, of what it already knows.

'If only we knew what we knew' is the lament of those who are aware that what is known to the individual members of the firm – often tacitly – is not necessarily known by the firm itself which therefore cannot act on such knowledge. The challenge then involves putting knowledge in a form that other members of the firm can understand and make use of. In other words, the challenge consists of converting an individual knowledge asset, tacitly held, into an organizational one, explicitly held (Nonaka and Takeuchi, 1994). Tacit knowledge then has to be 'captured' and codified to become an object external to individuals, capable of being stored and retrieved by other members of the organization – itself also often viewed as a stable object.

From this perspective, knowledge management seeks to address two issues: (1) How far should knowledge be articulated for a given purpose? (2) Who can it then be shared with? The assumption is that firms, like individuals, inevitably 'know more than they can say' (Polanyi, 1958), but that in practice they can be induced to 'say more'. This translates into a concern with knowledge *capture*, i.e. getting individuals to articulate what is in their heads so that it can be recorded, knowledge *codification*, getting this knowledge stabilized and intelligibly structured, and knowledge *sharing*, making it available to other individuals. Articulated knowledge now becomes an object that can be embedded in some physical substrate and stored, accessed, and retrieved with varying degrees of efficiency, independently of a knower.

At the other end of the continuum knowledge always remains internal to an intelligent agent – i.e. embodied – and shapes both its expectations and its disposition to act (Arrow, 1974). Here, what gets articulated and externalized by an agent is only ever *data* with varying levels of information content, not knowledge (Boisot and Canals, 2004). Data can be thought of as a set of distinguishable states that can register with other agents and from which they may be able to extract information. Taking knowledge to be a dispositional property of agent activity leads us to conclude that the Library of Congress does not, strictly speaking, store knowledge, but data with a high information content. An agent's disposition to action is shaped by incoming stimuli that register with it as data and interact with its prior knowledge to yield an interpretation of the stimuli and to suggest a possible response to them. To the extent that the agent's expectational state aligns with the actual states of the world, its response will be adaptive and its chances of survival in the world improve. Effective alignment may be undermined by insufficient or misleading data or a distortion of the data by the affective, ethical, or conceptual filters that the agent applies to it (Clark, 1997). How stringent an alignment is actually required will depend on how 'forbearing' the environment the agent finds itself in turns out to be. Some misalignments are more likely to threaten the agent's survival prospects than others – as Popper put it, at some point 'reality kicks back' (Popper, 1972). The realist will argue that alignment is both necessary and possible (Bhaskar, 1975). The constructivist will argue that the belief in an alignment is an illusion and that we have managed to survive quite well until now with little indication of how aligned our beliefs about the world will turn out to be in practice (Von Glasersfeld, 1995; Spender 1996).

Some of the incoming stimuli experienced by a given agent are generated by other agents who are also trying to make sense of things and adapt. What these subsequently emit as stimuli is the output of their own sense making efforts. The receiving agent then has two sources of inputs: (1) those coming from the natural world in an un-interpreted form; (2) those coming from the social world in an interpreted form. The challenge of collective sense making is to achieve some measure of alignment across agents' respective interpretations of both kinds of inputs (Weick, 1993). Clearly, as complexity – both social and natural – goes up, this becomes more difficult. With more degrees of freedom, the range of possible interpretations increases and these begin to diverge. We can frame the challenge of collective sense making and of social computation in general – of getting aligned with the relevant states of the world over time – as one of *organizational learning*. Such learning does not always deliver a better alignment. It can be superstitious (March, 1991) or driven by power relationships (Foucault, 1969). To the extent that social complexity exceeds natural complexity, it is more likely to lead to distortions of the learning process, manifesting itself in both political and commercial organizations as ideology, dogma, and prejudice – over-simplifications that restore tractability to social computational processes at the expense of their alignment with social realities.

We place the techno-economic approach to knowledge management at the knowledge-as-object end of the continuum and the ecological approach at the knowledge-as-agent end. The organizational approach would fit somewhere in between. How compatible are these different perspectives on knowledge management? Are we required to choose between them? If not, how might they be reconciled? The first yields a view of knowledge as a stock of objects available to agents, the second a view of knowledge as process – a flow of agent activity (Csikszentmihalyi, 1988).

Knowledge management as a response to growing complexity: a critique

Knowledge management is to date more a set of practices than an intellectual discipline. In spite of a proliferation of ICT-related tools that supports such practices, the subject still lacks a clear set of foundational concepts concerning the nature of knowledge that scholars and practitioners can agree upon. Modern physics took off with the stabilization of the concept of energy (Mirowski, 1989), modern chemistry with the development by Mendeleev of the periodic table, and biology with the modern synthesis of Darwin and Mendel. But where is the foundational concept of knowledge that can give us lift off? Whereas Nonaka and Takeuchi build on the Platonic view of knowledge as justified true beliefs (Nonaka and Takeuchi, 1994), a pragmatic approach to knowledge takes it to be that subset of your beliefs that you expect to deliver results when you act upon them, whether or not these turn out to be true. In the first scheme, knowledge-as-truth is the criterion; in the second, knowledge becomes dispositional and a property of an adaptive agent. But in this second scheme, what do we mean by *acting*? What is the nature and strength of my belief, for example, if it leads me to buy insurance or take out an option? What is the epistemic status of the knowledge that I am acting upon? In these cases, by my action, am I not, in effect, acknowledging my ignorance in the face of uncertainty and complexity?

To the extent that knowledge management wishes to accommodate a pragmatic approach, it is led to adopt a more ecumenical view of knowledge than, say, science does. Science will only count as valid knowledge which has undergone a rigorous and socially controlled process of codification and abstraction (Boisot, 1995, 1998), endorsing what proves robust and facilitates prediction. But other kinds of knowledge, anecdotal, affective, moral, etc. even if more fragile and tentative, also form a basis for effective action. In many cases predictability is a luxury that we cannot afford given the time available to react adaptively. Under these circumstances, we would be quite happy to settle for anticipation. We may not be able to locate an emergent threat or an opportunity with any great degree of precision (prediction), but we would be grateful enough to be able to sense its coming so as to recognize it in good time (anticipation). Some form of adaptation may then still be possible. Unfortunately, knowledge management's ecumenism is paid for in the coin of dross. Since more data, information and knowledge is always deemed to be better than less, knowledge management often does not know where to stop. Typically, more is retained than is needed – sometimes much more – and more is deemed necessary than is actually ever used. A Freudian might be tempted to describe the discipline as anal retentive.

This brings us back to our initial concern. Where the dosage is controlled, increases in knowledge allow us to respond adaptively to increases in complexity, hence the need for, and relevance of, knowledge management. But where the dosage is not controlled, current knowledge management practices may merely add to the complexity they are supposed to deal with. Much of ICT-driven knowledge management, for example, is data-increasing rather than knowledge-increasing and may be compounding rather than addressing the challenge. Unfortunately, knowledge management scholars remain divided on the question of how data, information and knowledge – some would add wisdom to the triplet – relate to each other, one reason being that they cannot agree on the meanings of these terms (Boisot and Canals, 2004). In the absence of some robust founding concepts, they are unlikely to.

How, then, might knowledge management help us meet the challenge of complexity? We now have data-processing-based measures of complexity – i.e. AIC – and information-based measures of its degree of structure (Gell-Mann, 1994). Could our growing understanding of complexity then itself help knowledge management become more relevant? Both address the problems of uncertainty, but in different ways. Plato required knowledge to have certainty as a key attribute. Yet we know that certainty is unattainable, especially under conditions of complexity. Waiting for some justifiable degree of certainty to be achieved before acting is a luxury that in practice we can rarely afford, and we are typically called upon to act on the basis of uncertain knowledge. Indeed, we often act on extraordinarily weak beliefs – hunches, vague intuitions, premonitions, etc. – as evidenced by our willingness to take out options or insurance contracts. Certainty is more often than not a subjective or intersubjective feeling that may or may not connect to a verifiable state of the world. In what follows we present an information-based framework that points to how the new complexity sciences might endow knowledge management with the theoretical backbone that it lacks. It offers an inclusive and pragmatic approach to understanding knowledge, one less concerned with Platonic questions of certainty and of justification and more oriented to biological processes of survival and effectiveness.

COMPLEXITY AND KNOWLEDGE: A CONCEPTUAL FRAMEWORK

The basics

The complexity sciences promote an objective view of complexity as an intrinsic property of states of the world. A subjective view of complexity looks at our capacity to make sense of the world given both its objective complexity and our cognitive and behavioural capacities to match it. Do my subjective representations of complex phenomena match their objective complexity? Do they do so fast enough to allow me to make sense of them and adapt (Weick, 1993)? Is the grainy satellite photo which I must act upon, for example, depicting a peaceful village settlement or a nuclear installation? Is the rowdy crowd that I see approaching friendly or hostile? This is knowledge as adaptive sense making as discussed in Chapter 16 of this volume. It comes in three different forms:

- *Embodied knowledge* (aka as phenomenology) – acquired dynamically through our sensory interactions with the world (Thelen and Smith, 1994). As I write these lines, I am sitting in a Starbucks coffee shop. I see chairs, tables, people, photographs on the wall, etc. I hear music and the sound of an espresso machine in the background, I taste the coffee. My body experiences the resistance of the chair that supports it while I sit. My arms and wrists experience the resistance of the laptop that rests on the table that I am writing on. I could go on – forever! Unless something anomalous crops up, I have no reason to doubt the validity of the knowledge that my senses are conveying to me as I interact with my surroundings. It forms the basis of what Polanyi referred to as personal knowledge. Most of it remains unarticulated and some of it will be inherently unarticulable (e.g. the taste of the coffee).[3]

- *Narrative knowledge* – that part of my embodied knowledge that I am capable of articulating and sharing with others through utterances, only some of which will be verbal – gossip, water cooler talk, commands, etc., but also grunts, sighs, voice pitch, and so on (Gazzaniga, 1992; Dunbar, 1996; Deacon, 1997). Only a tiny fraction of our embodied knowledge ever gets narrated. Until the discovery of radio waves, narrative knowledge facilitated and amplified social coordination across a physical space the size of which was defined by the reach of the human voice. The test for the validity of the knowledge conveyed through narrative is its alignment with the prior experience of those it reaches. In primary groups, such alignment is usually not hard to achieve. As the group grows larger and more heterogenous, however, securing alignment becomes more challenging.[4]
- *Abstract-symbolic knowledge* – those elements of my narratable knowledge exhibiting sufficient recurrent regularities that, in addition to articulating them, I can formalize them in such a way that they can reliably be generalized and applied across a range of different situations – either by myself or by others. Formalizing abstract-symbolic knowledge typically involves compressing it into a more compact representation than narrative typically requires, one that, when inscribed in some durable medium such as stone or paper, can be conveyed to others across vast stretches of space and time at low cost. Through repeated and varied applications, such knowledge – whether in verbal or inscribed form – gradually gets validated and acquires something of an objective status. It becomes knowledge that others are entitled to rely upon in drawing inferences or making predictions (Daston and Galison, 2008).

Although no clear dividing line separates the three kinds of knowledge, we make sense of the world by seamlessly integrating them. Piloting a wide-bodied aircraft, for example, is a complex task that requires you to integrate your body's sense of acceleration/deceleration (embodied knowledge), verbal instructions from air-traffic control (narrative knowledge) and what the countless dials on your control panel are conveying to you about the state of your aircraft (abstract-symbolic knowledge). Yet even as simple a task as telling someone the time involves moving your arm so as to bring your wristwatch into view (embodied knowledge), interpreting the abstract symbols on the watch face (abstract-symbolic knowledge) and translating this interpretation into the appropriate utterances (narrative knowledge).

The move from embodied to narrative and thence to abstract-symbolic knowledge saves on the time and effort required to process and transmit data. It does so by capturing essential information and shedding redundant data. The resulting economies can speed up adaptive responses. Yet whether responses are indeed adaptive depends on whether the move is information-preserving. Where that information resides in readily accessible empirical regularities, the process of articulating and structuring knowledge is a simple one that is readily performed. But where the regularities are elusive – i.e. the algorithmic information complexity (AIC) is high – the process is much more challenging and one runs the risk of losing relevant information instead of merely shedding redundant data. Knowledge and complexity are thus intimately related. Where complexity stands in the way of knowing, we can deal with it either by reducing it or by absorbing it. We reduce complexity by deploying cognitive strategies that give it structure. We absorb it by deploying appropriate behavioural strategies, often in coordination with others (Boisot and Child, 1999). Since our focus is on knowledge management, in what follows we only deal with the first.

Reducing complexity involves discerning stable structures in the flux of experience – i.e. developing insight. As intelligent systems, we do this through the twin processes of discrimination and association (Hahn and

Chater, 1997) which we re-label respectively *codification* and *abstraction*. The first helps us to clearly distinguish between categories so that we can rapidly assign phenomena to these. The second, by treating things that are different as if they were the same (Dretske, 1981) reduces the number of categories that we need to draw upon to categorize phenomena. Taken together, codification and abstraction speed up data processing and facilitate adaptation. Furthermore, as our knowledge becomes more structured through successive acts of codification and abstraction, it becomes more compact, more readily diffusible and hence more easily shared. We present this relationship between codification, abstraction and diffusion in a three-dimensional space called the Information-Space or *I-Space* (Boisot, 1995; 1998) that is depicted in Figure 25.1. As indicated by the curve in the diagram, the higher the levels of codification and abstraction, the larger the proportion of a given population of agents to which a message can be diffused per unit of time. In the I-Space, an agent can be any organized entity that exhibits agency – individual human beings, firms, nation states, etc. If we populate the diffusion scale with individual human beings, for example, we can choose to explore the information flows within a single organization. If we populate it with firms, on the other hand, we can look at information flows within an industry or a strategic alliance.

The social learning cycle

Over time there is a tendency for collectively useful knowledge to move through the I-Space, first in the direction of complexity reduction, that is, of increasing codification and abstraction and then second, in the direction of greater diffusion. In the case of scientific knowledge, for example, the need for parsimonious explanations favours increasing codification and abstraction. Indeed, such a move provides one of the essential criteria for what constitutes a scientific explanation (Hempel, 1966). Data that is not information-bearing – i.e. noise – gets discarded to achieve more compact

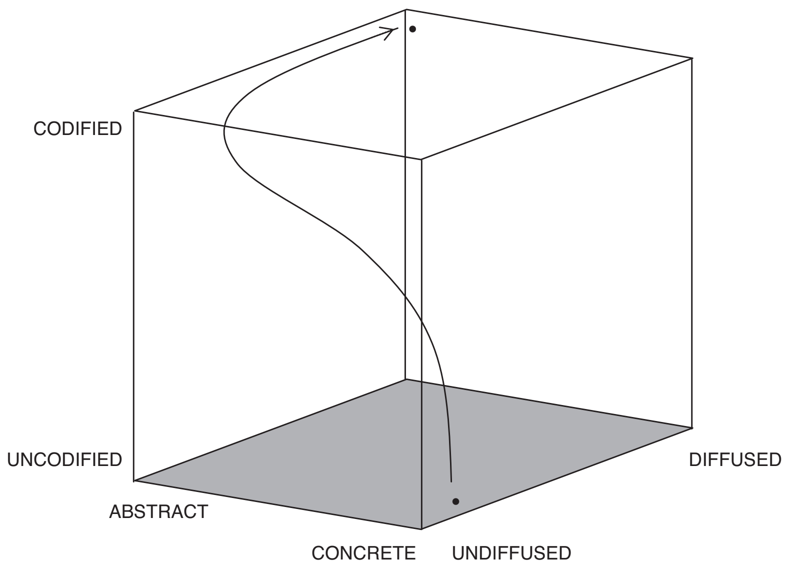

Figure 25.1 The I-Space

and hence more transmissible knowledge representations. The move, however, sacrifices context and richness and may threaten the coherence of knowledge so structured. Structured knowledge may be more diffusible but, as any high school math student will tell you, its very compactness may stand in the way of its intelligibility (Boisot, 1998); some face-to-face interaction allowing feedback processes to restore context may then be necessary to make sense of it. If the knowledge is useful there will be pressures to get it shared and this may entail its further codification and abstraction. But diffusing knowledge de-contextualizes it, often making it hard to understand. Furthermore, if such knowledge is to get absorbed and applied, there is often a need to embed it in a new context. Codification, abstraction and diffusion, therefore, are not the end points of a social learning process. If it is to be used, structured knowledge must also get internalized. The total process traces out a six-step *Social Learning Cycle* (SLC) in the I-Space as depicted schematically in Figure 25.2 and elaborated in Table 25.1.

The SLC can take on different shapes and sizes to reflect the learning dispositions of the various populations it describes. After all, learning takes time and effort, and not all situations will warrant it. Do the benefits of learning justify the investments required? If so, how does one extract value from such investments? *Economic* value combines utility and scarcity. In the I-Space, the move towards a greater codification and abstraction of knowledge, by reducing the complexity one has to deal with, generates utility. Codification makes knowledge more stable and robust, and also allows it to be either readily stored or easily transmitted. Abstraction makes knowledge more generalizable, allowing it to find application outside the context in which it arises. But at the same time, codification and abstraction, by making knowledge more diffusible, threaten to reduce its scarcity and hence its value to its possessor useless unless it can be harnessed to network effects. Depending on whether or not effective barriers to the diffusion of knowledge can be erected, the value extracted from the SLC thus accrues either to a subsection of the agent population or to the

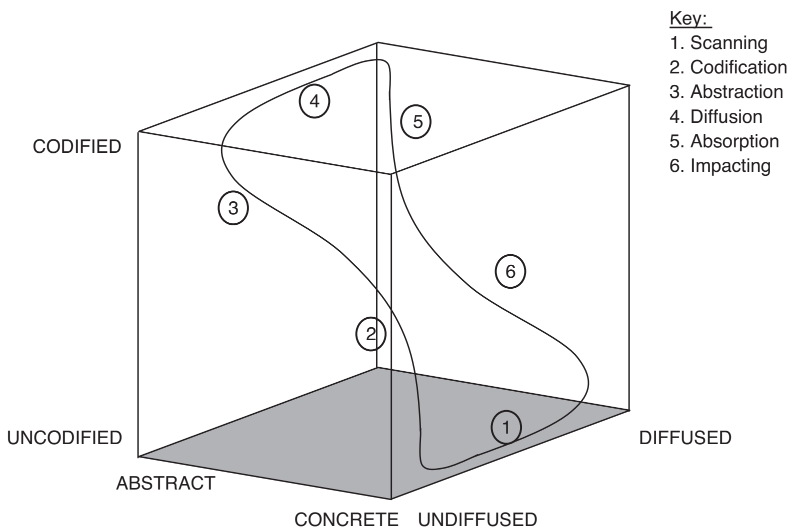

Figure 25.2 The social learning cycle

Table 25.1: The Six Steps of the Social Learning Cycle.

1. Scanning	A leftward movement in the I-Space that converts data available to others – threats, opportunities, etc. – into novel and insightful patterns that are relatively undiffused
2. Codification	A gradual articulation of initially fuzzy patterns into clear, compact, and robust representations that can be manipulated and stored. This is an exercise in data compression that moves it up the I-Space
3. Abstraction	Extracting from patterns their invariant and generalizable features. This results in further data compression and moves data from the front of the I-Space to the back.
4. Diffusion	A rightward shift of data – compressed or otherwise – across a population of agents located along the diffusion dimension of the I-Space
5. Absorption	The internalization and contextualization of data through acts of assimilation to existing schema. This entails a downward movement in the I-Space, one in which data gets interpreted
6. Impacting	A movement from the back of the I-Space towards the front in which data at varying levels of codification and abstraction is applied to concreted situation

population as a whole. In the first case, the relationship between agents is more likely to be competitive than in the second where all share the relevant knowledge.

Complexity in the I-Space

How does complexity manifest itself in the I-Space? If we take complexity to be a function of the number of elements in interaction, then we can locate complexity where the number of interacting elements is large. Where the interactions exhibit regularities and hence become predictable, however, we have a gain in structure and a consequent reduction in complexity. What do we take to be interacting elements in the I-Space? The I-Space describes the flow of information-bearing *data* across a population of interacting agents. How bits of data relate to each other – their interaction – defines their information content, so that we can take bits of data as one set of interacting elements and individual agents as another.

Data: It is data that diffuses across a population, data that is hopefully information-bearing. But what is the relationship between data and information on the one hand and knowledge on the other? Data that is information-bearing, when absorbed and applied, has the effect of modifying an agent's knowledge base and its disposition to act. The data can either emanate directly from the natural world in the form of physical stimuli, or from other agents in the form of a language, verbal or nonverbal.

Agents: When agents communicate with each other they can be said to be interacting. The I-Space is populated by agents who have been placed on the diffusion scale essentially because they have reason to interact with each other. Whether their interaction is structured or not depends in part on the way that information is distributed within the population and in part on the latter's size. Interactions within a large population are more likely to be complex than those within a small one.

The complexity that we associate with interacting bits – i.e. data – is *cognitive*. If, as AIC suggests, complexity can be measured by the amount of data processing than it entails, then we can say than uncodified knowledge entails more data processing than codified knowledge. It takes more data processing to distinguish between categories and assign event to them when both the categories and the events are fuzzy than when they are crisp (Boisot and Li, 2005). Yet, as we saw above, AIC is an aggregate measure of entropy that does not separate out the complexity generated by the structure of phenomena from that generated by the noise in which they are embedded. It is a measure of crude complexity. Gell-Mann's effective complexity, by contrast, measures the amount of data processing entailed by the regularities residing in phenomena – in their degree of structure. In the I-Space, more concrete phenomena, being apprehended through a larger number of interacting categories than abstract ones, are characterized by higher levels of effective complexity.

The complexity that we associate with interacting agents, by contrast, is *social*. Data processing measures of complexity, however, still apply. Other things being equal, it takes more data processing to capture the interactions of a large population of agents than of a small one. Furthermore, higher levels of data processing are called for when those interactions are unstructured than when they are structured. Structuring agent interactions so as to reduce their complexity is what formalizing organization is all about. The organizational equivalents of codification and abstraction are differentiation and integration, the drivers of the formalization process (Lawrence and Lorsch, 1967). The larger the population involved, the greater the need for formalization. The alternative is to reduce the extent to which agents either need to or can interact by subdividing the population into independent groups – in large organizations they are placed in departments or divisions.

As indicated in Figure 25.3, we now have two quite distinct avenues open to us if we want to reduce organizational complexity: The first is cognitive and moves us up the I-Space towards higher levels of codification, of abstraction, and hence of structure – organizational structuring, for example, calls for a codification of roles and standard operating procedures and their generalization (abstraction) across a population. The second is social and moves us towards either more structured and controlled social interactions or a more balkanized social structure. Both of these moves reduce the number of interacting agents, thus shifting social interaction towards the left along the diffusion scale, where the rate of diffusion of information-bearing data can be brought under some degree of control. To control the flow of information is to limit its diffusion to specific agents and/or circumstances. One may want to control the diffusion of information so as to achieve better coordination or, for good or

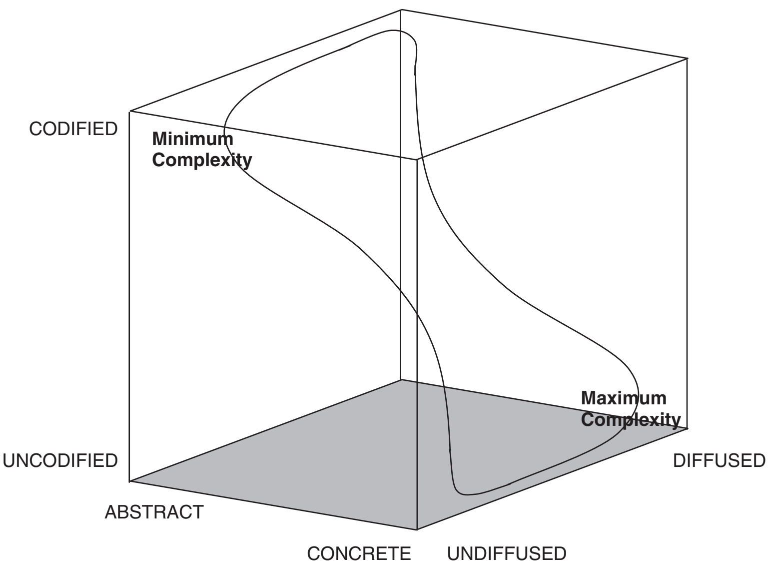

Figure 25.3 Three regimes in the I-Space

ill, to keep different groups of agents from interacting with each other. Typically, cognitive and social strategies work in tandem to reduce organizational complexity.

The dynamics of the SLC suggests that we will not always *want* to reduce organizational complexity. Ashby's law of requisite variety states that if a system is to survive, it must be able to generate from inside a variety that can match that which it confronts outside (Ashby, 1956). For variety read complexity. If globalization increases the complexity that we have to deal with, do we not in fact need more complex organizations to match it? If so, do the possibilities offered by new information and communication technologies (ICTs) contribute to the solution or to the problem? We turn to this next.

THE NEW ICTS

For any given level of codification and abstraction, the new ICTs increase the volume of data that can be processed and transmitted and increase the size of the population that can be reached per unit of time. This shows up as a rightward shift of the diffusion curve along the diffusion dimension of the I-Space as indicated in Figure 25.4. Economists would describe this as a shift in the supply curve for data.

The figure highlights two distinct effects of this curve shift: a *diffusion effect* and a *bandwidth effect*. The diffusion effect, we have just discussed: an increase in the number of people that can be reached per unit of time, whatever the level of codification and abstraction of the message. The bandwidth effect is less obvious. It suggests that a population of a given size can be reached at a lower level of codification and abstraction than hitherto. Voices, pictures or video clips on YouTube replace terse textual or quantitative descriptions. Snippets of embodied and narrative knowledge can then start to flow as rapidly and extensively within a given population as abstract-symbolic knowledge. Unfortunately, one then butts up against the ultimate limitation on such voluminous transfers: increase the bandwidth and you may effectively end up increasing the claims on the scarcest of your cognitive resources, namely, your capacity for attention (Simon, 1986). Extracting information from data in a timely fashion is the challenge. There will be times when extracting information from high bandwidth information will be efficient. I can immediately recognize a photo of my wife, for example, where it might take me several hours to realize that a detailed written description of what the photo conveys actually refers to her. But that is because I am already familiar with what my wife looks like. On the other hand I am more likely to get an accurate sense of the support garnered by a presidential candidate from the number of people who voted for her – an abstract symbolic representation – than from a photograph of her supporters all assembled. Here, the parsimony achieved by compressing knowledge into abstract-symbolic forms of representations releases attention for other things.

The new ICTs simultaneously facilitate the processing of data and add to the data to be processed. With increased bandwidth, both structured and unstructured data can now be transmitted with ease. But the real limit to bandwidth resides inside our heads: we can only process so much data at a time without blowing a fuse. Increasing the bandwidth increases the volume of data to be processed. Yet unless it is processed before it reaches us, it will often only increase the complexity we face. There is no free lunch.

THE FUTURE OF KNOWLEDGE MANAGEMENT IN A COMPLEX WORLD

Knowledge management in the I-Space

How far do the practices of knowledge management help to meet the challenges of

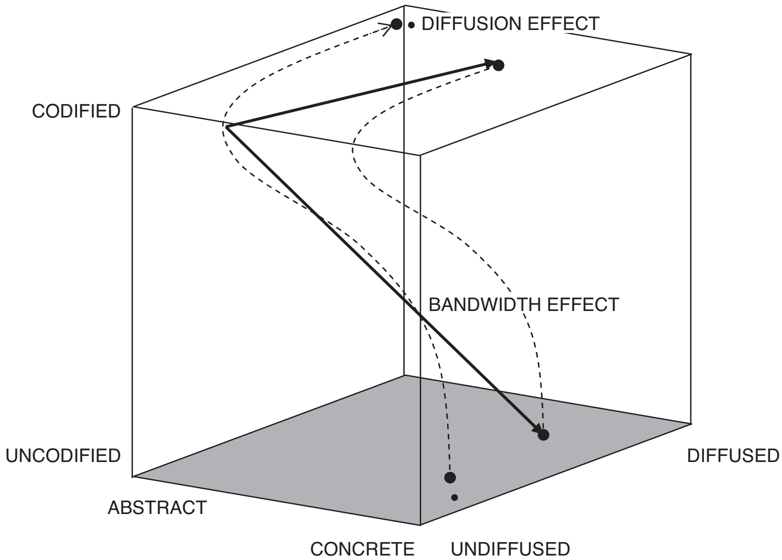

Figure 25.4 The impact of ICTs in the I-Space

increasing complexity? In *Blown to Bits*, Evans and Wuster (2000) tell us that the old trade-off between the richness and the reach of knowledge has been abolished. With the new ICTs we can now have both. A complexity perspective suggests otherwise. Richness typically refers to knowledge that is complex, concrete and largely uncodified. Reach refers to its diffusibility. As with rich food, rich data taken in large quantities will end up making us informationally obese, often slowing us down at the very moment that the complexity we encounter may require us to be lean and agile. Leanness requires us to be more selective in the data we process. After all, as we have seen, we make sense of the world by integrating embodied, narrative and abstract-symbolic knowledge in ways that achieves *coherence* – what we experience must either align with or modify our existing models and expectations in meaningful ways. The challenge for knowledge management is to enhance our capacities to absorb and process data without compromising our ability to achieve coherence. If much of the sense making literature has tended to focus on the link between embodied and narrative knowledge (Weick, 1993; Czarniawska, 1997; Snowden undated), the practitioner literature on knowledge management has concentrated on the link between narrative and abstract-symbolic knowledge (Stefik, 1995). Coherence requires that these two sides of knowledge management be brought together. When they are we will discover that *the management of knowledge is co-extensive with the management of complexity*. Framing this claim in the language of the I-Space we see that knowledge management consists of managing one or more SLCs for maximum value through a judicious mix of complexity reduction and complexity absorption. A simple knowledge management prescription here would be: reduce complexity where you can do so at a low cost; absorb complexity where you can't.

NOTES

1 The point holds true for natural systems studied above the Planck scale. At that scale, quantum effects kick in to make the observer part of the system (Omnès, 1999).

2 China developed a printing technology based on woodblock printing in the eighth century and one based on movable type in the eleventh. The complexity of Chinese characters, however, prevented China from exploiting this technology until the late nineteenth century. For this reason, printing technology did not impact domestic rates of literacy the way that Gutenberg's invention did in Europe (DeFrancis, 1984; Hannas, 1997).

3 Polanyi has focused primarily on that tacit component of our knowledge that we find hard or impossible to articulate (Polanyi, 1958). But the term 'tacit' also covers large tracts of knowledge that could either be articulated but are not because the costs and benefits of doing so are stacked against it or because it is so widely shared that articulation becomes superfluous.

4 It was the need to secure the alignment of large crowds in the agora that pushed the Greeks of fifth century Athens to place such a premium on rhetoric (Fine, 1983).

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26

Complexity and Innovation

Pierpaolo Andriani

INTRODUCTION

Innovation is about turning knowledge and new ideas into social and economic changes through the deployment of new technologies. Contrarily to more traditional factors of production – land, capital and labour – knowledge is more likely to give rise to positive feedback and network effects (Romer, 1986, 1994; Arthur, 1988, 1990). The more a society turns knowledge-intensive, the more dominant network effects become. The dynamics that these effects generate 'is lopsided, discontinuous, disharmonious by nature ... studded with violent outbursts and catastrophes ... more like a series of explosions than a gentle, though incessant, transformation' (Schumpeter, 1939: 102). Such is the world of innovation. This world is characterized by nonlinear dynamics, emergent properties, discontinuities and self-organizing patterns that once established become the platform for further disruptions. Complexity theory provides conceptual tools to understand this world (see the foundations section of this volume).

Hence the question: why isn't complexity more dominant in innovation studies? For a long time innovation studies have been dominated by neo-classical economics. In spite of this, complexity thinking runs deep through the history of innovation. Schumpeter's great contribution (1934, 1939) is to have connected the role of innovation with economic growth and social change. His analysis rejected simplistic circular flow and equilibrium theories and introduced topics strongly resonant with complexity ideas such as the chaotic dynamics of radical change, extreme events and the bottom-up, self-organizing engine of capitalism: entrepreneurship.

The emergence of the Internet and of the 'network society' (Castells, 2000) has been accompanied by the development of the 'science of networks' (Watts, 2003; Newman et al., 2006: 2008). This is probably the most important evolution in innovation studies in the past decade. It brought about a shift in focus from the manufacturer-centric to network-centric approaches (Powell et al., 1996; Iansiti and Levien, 2004). The shift has given rise to new approaches which reach beyond the firm and its boundary as the main subject of the innovation process and take the network as the new unit of analysis. By linking traditional actors, such as firms and institutions, with new agents, such as communities, users and technological platforms, these new innovation networks have generated a 'network of networks', a massively interdependent 'organism' that links together companies, research institutions, inventors, self-organizing communities, regulatory institutions and technologies. This super-network generates the collective interdependent system of technologies known as the technosphere.

The emergence of a globally connected technosphere is likely to represent a fundamental discontinuity in technology history and innovation studies and poses a number of crucial issues: Are traditional tools based on linear science appropriate to deal with the emergence and evolution of a globally interdependent technosphere? How does the collective set of technologies co-construct itself? What is the role of self-organizing networks in the expansion of the technosphere? I will explore these issues in the following sections. The description of the universal properties of the technosphere as seen through a complexity theory lens concludes this chapter.

Although innovation studies is an ideal field for the application of complex systems-based models, the number of scholarly works that directly apply complexity to innovation is relatively small. They can be grouped into the following categories.

Works that focus on self-organization and emergent properties

This literature takes its move from the rejection of neo-classical models, which are based on assumptions of equilibrium, gradualism and use reductionist methodologies. At the opposite end of reductionist frameworks sit evolutionary frameworks, based on path-dependency, emergent properties at multiple level of aggregation and self-organization. In these models the arrow of causality go from components to wholes and from wholes to components (Juarrero, 1999; Noble, 2006; Ulanowicz, 2009). One of the main concerns of evolutionary frameworks is the understanding and modelling of discontinuities, most often triggered by radical innovations. Nelson and Winter's (1982) evolutionary economics frameworks, Dosi's (1982) technological trajectories, Abernathy and Utterback's (1978) dominant design model draw from Schumpeter's seminal work and (often implicitly) build a complexity-based theory of innovation-driven endogenous change in the economy (Foster, 2000). Technological discontinuities give rise to nonlinear effects such as technological lock-ins (David, 1985), externalities and positive feedback dynamic (Romer, 1986, 1994; Arthur, 1990) and rely on *punctuated equilibria* models (Gould and Eldredge, 1977; Tushman and Anderson, 1986; Tushman et al., 1986; Mokyr, 1990; Gersick, 1991). The modelling of technological discontinuities (Saviotti and Mani, 1995, 1996) show the fundamental importance of technological and organizational diversity (Mokyr, 1990; Saviotti, 1995, 1996; Allen, 1997; Grabher and Stark, 1997) in endogenous models of innovations. A parallel stream of complexity studies originates from Simon's (1962) nearly-decomposability model (see Baldwin and Clark (2000) for a review).

Works that focus on networks

This is a rich area of research with multiple streams. This literature can be summarily divided into literature that examine the impact of collaboration and knowledge diffusion on innovation within networks (Powell et al., 1996; Pyka and Küppers, 2002; Schilling and Phelps, 2005) and literature that focuses on the relationship between topology of non-random networks and innovation diffusion (Cowan, 2006; Frenken, 2006). These works overlap with the literature on simulation and modelling. Complexity can legitimately claim to have provided a third method for scientific inquiry: computer simulation. Among the simulation approaches that have been used in innovation studies we cite: Cellular Automata (Kauffman, 1995), fitness landscape and *NK* models (Kauffman, 1995; Gavetti and Levinthal, 2000; Rivkin, 2000; Fleming and Sorenson, 2001); agent-based modelling frameworks (Gilbert et al., 2001;

Fagiolo and Dosi, 2003; Dawid, 2004; Pyka and Fagiolo, 2005; Frenken, 2006).

Other works apply aspects of complexity theory such as chaos theory (Cheng and Van de Ven, 1996) and fractal/allometric theory (Bettencourt et al., 2007). This is probably the least developed area and, at the same time, one of the most promising.

LINEAR MODELS, GAUSSIAN TOOLS AND THE INTERDEPENDENT TECHNOSPHERE

A large part of the literature on innovation tends to treat the technosphere as an additive aggregate of individual technologies, developed by individual companies or institutions. A cursory look at the literature, take for instance the *Oxford Handbook on Innovation* (Fagerberg et al., 2005), reveals scant attention to the issue of collective interdependence and rules of expansion of the technosphere.

Many of these traditional approaches share the underlying idea that the variability of the innovation world is somehow limited and that a statistically accurate analysis of the history of innovation can provide the salient features of the processes concerned with innovation. Under the hypothesis of finite variability, lessons learnt from the past are applied to predict the future and the regularities found at the aggregate level are considered to be valid at the single agent level.

The finite variability approaches ultimately rely on the General Linear Reality (GLR) model (Abbot, 2001):

> The phrase 'general linear reality' denotes a way of thinking about how society works. This mentality arises through treating linear models as representations of the actual social world.
>
> $$y = Xb + u$$
>
> The social world consists of fixed entities (the units of analysis) that have attributes (the variables). These attributes interact … to create outcomes, themselves measurable as attributes of the fixed entities.

The GLR has encouraged the view that innovation is an exogenous variable in the economic landscape. According to this view, innovation affects the attributes of the entities but not the entities themselves. Gradualism in innovation is consistent with this view.

Typological thinking represents the consequence of this approach. It reduces the complexity and variability of technological change and organizational innovation to a limited set of categories that ultimately follow principles of efficiency and gradualism. For instance, Mokyr (1998) comments that:

> … economics' knee-jerk response is to regard technological diversity [generated by innovation] as a source of inefficiency: if a product under very similar circumstances is made in different ways, our first suspicion as economists is that at least one of the producers is doing something wrong. … An evolutionary perspective tends to regard variability as a source of innovation and long-run successful performance.

In this reductionist view of technological change, selection processes are efficient and optimize outcomes by selecting the best option.[1]

Categorization and taxonomical exercises (Pavitt, 1984) often reify the limited variability of the sample chosen. The perennial discussion about whether large firms are more or less innovative than SMEs, the various classification of SMEs into categories in order to ascertain the underlying innovation patterns are examples of the limited variability view (i.e. see De Jong and Marsili, 2006). One can raise the objection that these works rely on hidden Gaussian assumptions, such as outliers elimination even when examining a reality that presents Paretian long tails (Andriani and McKelvey, 2009); second, they often and implicitly rely on the concept of 'species' (for a critique in biology see Margulis and Sagan, 2002) and omology (Lorentz, 1973). As horizontal transfer (Woese, 2004) in technological innovation is dominant, the basis for classification is questionable. Classificatory studies that partition firms into abstract categories such as, low/high tech, MNEs/SMEs, etc. are useful to identify minimum common denominator properties among the set under study. However, they tend to ignore the idiosyncratic elements that resist classification. These differences constitute the pool from which innovations arise and redefine firm populations.

Many studies on innovation also rely on the time-honoured tradition of taking samples of firms, organizations, or other types of 'agents' to prove or disprove hypotheses via statistical significance testing (SST). This runs into a long series of problems. First, SST is based on a dichotomous view of the world, null-hypothesis or the opposite. Instead, the world of innovation is not dichotomic as it is characterized by strong uncertainty and unbounded variability that is difficult to reduce to an either-or formulation. Second, given the inherent importance of contextual conditions, and therefore the nearly unlimited variability of any sample, the possibility of finding a large enough number of cases to prove or disprove a statistically formulated hypothesis is low. Third, even proving (or disproving) a null-hypothesis at best demonstrates a correlation and says little about causal relationships. Starbuck (2006: 49) comments:

> Choosing two variables utterly at random, a researcher has 2-to-1 odds of finding a significant correlation on the first try, and 24-to-1 odds of finding a significant correlation within three tries. … the main inference I drew from these statistics was that the social sciences are drowning in statistically significant but meaningless noise.

Reliance on central tendencies is more problematic in innovation studies than in other fields of management and economic studies. The normalization of samples for statistical analysis tends to eliminate outliers which in a gradualistic view of societal change are attributed to measurement errors or other spurious effects. Since radical innovation is a discontinuity and appears to be an outlier, the result is to throw out the baby with the bathwater. Popular books in the management literature which claim to explain innovation and how to become innovative, such as *In Search of Excellence* (Peters and Waterman, 1982), *Built to Last* (Collins and Porras, 2002), *Good to Great* (Collins, 2001), suffers from fundamental analytical flaws, well explained in *The Halo Effect* (Olk and Rosenzweig, 2007). Even works that apply complexity theory tools and methods such as *NK* landscape modelling often fall in the trap of central tendency (see for instance Fleming and Sorenson (2001) on modelling innovation via *NK* landscape).

Moreover, adopting a reductionist view of the world leads to spurious connections between statistical results and practical actions. The assumed normality of social/economic phenomena leads to a representation of the system under analysis as a set of representative agents with limited variability. The statistical properties of the sample embodied in the representative agents are then *de facto* applied to the real agents that form the populations. As a consequence, policy actions based on the representative agents are then transferred from the abstract world of statistical significance tests to the real world. In reality: *Neither the industry-level graphs nor the group – level graphs [make] statements relevant for individual companies* (Cool and Schendel, 1988).

To sum up: general linear reality models, typological thinking and finite variance statistics are appropriate tools to analyse a social world based on gradualism, equilibrium and finite variability. Hence, it is no surprise that the world of innovation and technology has been for a long time treated as an exogenous *black box* that disturbs the harmony of the whole.

THE DYNAMICS OF THE TECHNOSPHERE

In this section I briefly discuss the dynamics of the emergence and evolution of the technosphere. I start by presenting two concepts rooted in complexity theory: positive feedback and recursivity. I trace the history of the concept of positive feedback in early writers on economics and technical change, focusing in particular on Schumpeter's work. Then I present some very recent works rooted in complexity theory that discuss how the technosphere originates and evolves.

Not a black box: The origin of positive feedback in early thinkers in technology and economics

Positive feedback, also known as cumulative causation, deviation amplification (Maruyama, 1963) and in economics as increasing returns, indicates a situation in which a process becomes self-reinforcing and spirals up in an explosive way. When the elements of the positive feedback loop achieve closure, the loop becomes autocatalytic (Eigen and Schuster, 1979), or in other terms autopoietic, i.e. capable of creating itself out of itself (Maturana and Varela, 1987; Arthur, 2009). The growth of a system under positive feedback usually follows a recursive dynamic known as scale-free, explored by Sornette (2000), Newman (2005) and Andriani and McKelvey (2009). Scale-free dynamics yield recursive systems. Recursivity indicates the propensity of a system to nest into a hierarchy of self-similar structures. A recursive system tends to be self-similar, that is its subsystems and their dynamical behaviours appear similar across multiple scales (Mandelbrot, 1982). Recursive dynamical systems driven by positive feedback dynamics show the universal signature of Paretian distributions. Positive feedback is a crucial mechanism in the history of innovation, but has rarely been considered as such. It represents an 'underground river' (Warsh, 2006) in the history of innovation and technology, which emerges from time to time to disappear under the crust of linear thinking and reductionist frameworks.

The story of increasing returns coincides with the very beginning of the history of economic growth, that is, with Adam Smith. Interested in economic growth and in the allocation of resources mechanism, Smith introduced an apparently irreconcilable contradiction at the heart of economics: the mechanism of allocation of scarce resources is governed by decreasing returns (powerfully described with the metaphor of the *invisible hand*), whereas the mechanism of growth depends on division of labour which is intrinsically based on increasing returns (the *pin factory* example). These two ideas have had very different histories. The *invisible hand* idea has become the foundation of modern economics. The *pin factory* instead has become a permanent thorn in the side of economics. Malthus, Ricardo and Stuart Mill and others dismissed the increasing returns mechanism implicit in the *pin factory* and built the foundation of classical economics on the diminishing returns mechanism that would put economics on solid scientific ground, except that it leaves economic growth largely unexplained.

The *underground river* of increasing returns did occasionally emerge with the work of Marx that defined economics as a *critical history of technology* and with Marshall's theory of *spillovers* and *external economies*. The latter was introduced to justify the survival of competitive markets in presence of increasing returns to scale due to specialization (division of labour). Marshall had correctly observed how technological learning and innovations would spill over the boundary of the local firm and benefit the entire district, thus preventing the increasing returns mechanism to degenerate into a monopoly. Marshall is the first to notice that space and social routines mediate the processes of technology diffusion and incremental innovations transforming the apparently linear and simple process of technology diffusion into a nonlinear and cluster-based problem.

The *underground river* re-emerged forcefully but briefly with Alwyn Young in 1928.

His paper is concerned with increasing returns associated with innovation. Based on the smithian *pin factory,* Young realized that the power of division of labour does not reside as much in increased efficiency, but rather in the potential of applying a fragment of activity to new uses. The famous sentence: '*one man draws out the wire, another straights it, a third cuts it, a fourth points it, a fifth grinds it at the top for receiving the head* ...' can be reinterpreted as a blueprint of generic activities that when mastered can be reapplied into contiguous technological or market sectors, thus generating waves of innovations. In a single stroke, Young transformed the closed world of economics, in which effects would strictly follow from premises given boundary conditions, into the open universe of complexity and innovation. In fact, once one makes innovation dependent on a process of unfolding specialization based on discovery of serendipitous applicability of existing techniques into new sectors, one creates an increasing self-expanding returns loop. The larger the available toolkit of specialized activities, the larger the probability of finding further applications. This generates income and enlarges the portfolio of activities, therefore restarting the loop. The important effect of specialization is not increased efficiency but the fact that specialization leads to 'radiation' of technologies and skills into new sectors, thereby driving innovation[2] (Jacobs, 2000).

Finally Romer's *new growth theory* (1994) makes the point that the segment of economics that deals with the fourth factor of production – knowledge – is characterized by abundance and non-rivalry: knowledge is inherently exposed to increasing returns dynamics. This point is critical for the understanding of the inequality of knowledge distribution and its tendency towards spatial concentration (Storper, 1997).

Schumpeter

Schumpeter opens a new trajectory in the study of social/economic systems and anticipates many of the themes that decades later would become accepted. To understand the revolutionary contributions of Schumpeter's thinking, one has to realize that economics has struggled with innovation, increasing returns and novelty because of deeply engrained assumptions:

> The typical economic model implicitly assumes that the set of goods in an economy never changes. ... [An] important stumbling block has been the deep philosophical resistance that humans feel toward the unavoidable local consequence of assuming that genuinely new things can happen at every juncture: the world as we know it is the result of a long string of chance outcomes. (Romer, 1994: 5)

By putting at the centre of his analysis the disruptive role of the entrepreneur, Schumpeter proposes a vision of capitalism which anticipates a Prigoginian far-from-equilibrium concept (Nicolis and Prigogine, 1989). In the *Instability of Capitalism* (1928), Schumpeter rejects the idea of equilibrium and suggests that a capitalist society can only survive in a disequilibrium state as it depends on successive waves of technological innovations to renew the economy and its sociological structures. Capitalism is intrinsically unstable and is a dissipative system. Schumpeter's deep understanding of history brings him to formulate a view of economic change based on the discontinuities triggered by radical innovations.

> Evidently, we must cease to think of it as by nature smooth and harmonious in the sense that rough passage and disharmonies present phenomena foreign to its mechanism and require special explanations by facts not embodied in its pure model. On the contrary, we must recognize that evolution is lopsided, discontinuous, disharmonious by nature – that the disharmony is inherent in the very modus operandi of the factors of progress. … the history of capitalism is studded with violent bursts and catastrophes which do not accord well with the alternative hypothesis we herewith discard, and the reader may well find that we have taken un-necessary trouble to come to the conclusion that evolution is a disturbance of existing structures and more like a series of explosions than a gentle, though incessant, transformation. (Schumpeter, 1939: 102)

By doing so Schumpeter introduces evolution (Foster, 2000) into economics and anticipates a punctuational view of economic change (Awan, 1991; Gersick, 1991).

The issue of novelty raises problems. Schumpeter understands that circular flow mechanisms are the direct descendent of conservation principles in classical physics and stand in the way of a correct understanding of entrepreneurship. The economy co-constructs its own structures. For instance, the entrepreneur that faces fixed costs to develop new technologies and launch new industries before revenues materialize can use the expectation of future revenues to access credit. This is a powerful increasing returns mechanism (O'Sullivan, 2005). Credit creation catalysis entrepreneurship that then generates the resources that feed credit. The economy builds itself out of itself.

The inherent instability of capitalism, constantly kept at the 'edge of chaos' by the endogenous forces of innovation and entrepreneurship lead Schumpeter to formulate his celebrated idea of *Creative Destruction:*

> The fundamental impulse that sets and keeps the capitalist engine in motion comes from the new consumers, goods, the new methods of production or transportation, the new markets, the new forms of industrial organization that capitalist enterprise creates. ... [T]he opening up of new markets, ..., and the organizational development from the craft shop and factory ... illustrates the same process of industrial mutation ... that incessantly revolutionizes the economic structure from within, incessantly destroying the old one, incessantly creating a new one. This process of Creative Destruction is the essential fact about capitalism. It is what capitalism consists in. (Schumpeter, 1950: 83)

Schumpeter introduces and explores several issues, which would be recognized as important only after his death. These include: the description of the capitalistic process as inherently unstable and far-from-equilibrium; the emphasis on the discontinuities introduced by technological change that redesign the rules of the game of economy and society; the interpretation of the role of change as due to multi-level causes that embrace the *micromotives* of the agents and the *macrobehavior* of systems (Schelling, 1978); the pluralistic and antireductionistic approach to multidisciplinary research drawing on sociology, history, philosophy and political sciences in addition to economics; the recognition of the power of evolutionary interpretations for understanding historical change processes;[3] the emphasis on extreme events as generative forces that create new structure via creative destruction. All of these struggled with the mathematical formalism then and now dominant in economics. Towards the end of his life Schumpeter gave up on the idea of economics as an exact science and on the role of mathematics as the only language of economics (Warsh, 2006). As Douglas North (1994) puts it: '*the price you pay for precision is inability to deal with real-world questions*'.

The expanding world of technology: Arthur's scheme

Brian Arthur is one of the most well known complexity thinkers and a pioneer in the study of increasing returns in the evolution of economies and technologies (1988, 1990). In *The Nature of Technology* (2009), Arthur proposes an evolutionary framework of technological development, based on three features: first, technologies form tree-like structures in which the combination and distribution of parts, that are other technologies, builds up the architecture of the *purposive* system we call a technology. In other words, technologies form nested recursive systems. Second, most new technologies show a recombinant nature. New technologies emerge by assembling already existing technologies in novel ways. Third, all technologies result from the exploitation of natural phenomena. Phenomena are the effects of laws of nature that regulate the way in which energy or information is exchanged or transformed.

In Arthur's view, these three properties of technological systems: recursiveness, recombination and phenomena-based, form an autopoietic, self-making system. Technologies are conceptualized as systems to transform technologies into even more complex technologies. The aforementioned loop is reinforced by the fact that technologies enable the discovery of further phenomena that are added to the stock of known phenomena and used to create/invent new technologies. This approach accounts for the virtuous conversation between science (discovery of new phenomena) and engineering (the utilization of phenomena) that has become common practice since the industrial revolution (Murmann, 2003; Mokyr, 2004).

> There is a nice circle of causality here. We can say that novel phenomena provide new technologies that uncover novel phenomena; or that novel technologies uncover new phenomena that lead to further technologies. Either way, the collectives of technology and of known phenomena advance in tandem. (p. 66)

The relationship between the economic system and the technological system is more than co-evolutionary. It is co-constructive. New economic domains emerge around new technological domains with economic demand playing a selective role on the expansion of the technological sphere.

The dynamics of co-construction of the technosphere

How does the technosphere co-construct itself? Stuart Kauffman (2000) suggests that constraints play a generative role in the expansion of the technosphere. Kauffman notes that the generation of any entity, from information to artefacts, involves a *constrained release of energy*, work.

Constrained means that some boundary conditions have to be in place to direct the transformation of energy into work. Following Juarrero (1999), we note that a pendulum consists of a mass tied to a string anchored to a fixed point. The resulting motion (oscillation) is a constrained free fall that ensues from the reduction of degrees of freedom. The whole (mass + string) delivers its energy in an orderly periodical motion (new phenomenon) that can be used as an oscillator to measure time and to build watches. Constraints enable the creation of more complex entities via the regulation of the delivery of energy. However, the question that Kauffman asks is where do constraints come from? It takes work to 'fabricate' the constraints that allow the conversion of energy into work. This suggests that we can reinterpret technological innovation as the generation of new constraints (i.e. technologies) that makes possible more sophisticated conversions of energy into work. But then, once new constraints are in place, more work can be extracted from the same amount of energy and the additional energy can be used to generate more constraints. The interplay between work and constraints reveals something deeper about the emergence of technological complexity. Echoing Prigogine, Kauffman notes that constraints work by utilizing undiscovered and unexploited far-from-equilibrium situations, or, in other words, energy gradients. In the field of energy generation, hydroelectric, wind and tidal energy are obvious examples.

> Nonequilibrium processes and structures of increasing diversity and complexity arise that constitute sources of energy and that measure, detect, and capture those sources of energy, build new structures that constitute constraints on the release of energy, and hence drive nonspontaneous processes to create more such diversifying and novel processes, structures, and energy sources. (2000: 98)

A falling mass is a spontaneous process. It liberates energy. The pendulum periodical trajectory is non-spontaneous insofar as it requires the presence of a constraint to arise. The non-equilibrium situation that is being exploited is still the same: a falling mass. But the constraint allows the discovery of a different form of energy delivery, this time ordered: periodical motion. Moreover, the invention of the pendulum enables the discovery and utilization of new more sophisticated sources of non-equilibrium (effects that depend on the harnessing of periodical motions), the invention of mechanical clocks, the escapement mechanism, the resolution of the problem of *Longitude* (Sobel, 1995). A new technology (i.e. the set of constraints that regulate controlled delivery of energy) is first, a device that builds on the discovery of new sources of non-equilibrium situations and enables the extraction of energy from it and, second, a new source of non-equilibrium in itself, that can therefore be utilized to build more sophisticated constraints. Constraints constitute the scaffolding of the technosphere into the adjacent unknown. By revealing new sources of disequilibrium, constraints effectively turn the adjacent possible into the new external layer of the technosphere.

Explaining the dynamics of constraints is crucial to understanding one of the most important issues in innovation studies: the clustering of innovation. Jane Jacobs provides a useful analogy:

> Sunlight falling on a desert barren of life heats sands and rocks, but when night falls, even that quantity of temporarily retained energy radiates outward. In this case, the passage of energy is swift, simple, and vanishing, leaving no evidence of the passage. It must have been like this when sunlight fell on earth's primordial rocks and empty seas before life began. ... Contrast that with energy flow through a well-developed forest ecosystem. In the forest, energy flow is anything but swift and simple, because of the diverse and roundabout ways that the system's web of teeming, interdependent organisms uses energy. Once sunlight is captured in the conduit, it's not only converted but repeatedly reconverted, combined and recombined, cycled and recycled, as energy/matter is passed around from organism to organism. (Jacobs, 2000: 46)

In this example, the tropical forest ecosystem constitutes a dense network of constraints which enables the use (or recycling) of the same amount of energy in multiple tasks. For example, a task like growing a leaf generates a gradient of energy in terms of micro differences of temperature, humidity and mass that parasites can exploit to build a new micro-environment, that then can be used by specialized bacteria, etc. Energy is not wasted, but recycled over and over again. The analogy can be used to illustrate the difference between zones endowed with little technological complexity (the desert) and others (the tropical forest) where a rich texture of entrepreneurship and technological constraints allows the conversion of energy (in the form of intellectual creativity and funding) into technologies. Even if Jane Jacobs never used the term 'constraint', it was implicit in her idea of 'one work lead[ing] to another' (1970, 1985). The generative power of diversity that Jacobs claims is the source of clustering of innovation is based on the positive feedback loop between the density of constraints (linked to diversity) and the generation of innovation. This results in autocatalytic loops that generates the clustering of innovation. This idea is her fundamental contribution to innovation and entrepreneurship literature.

THE EMERGENCE OF THE TECHNOSPHERE AND DISTRIBUTED NETWORKS

Powell (2005) states that, '*Research on the relationship between networks and innovation is a relatively recent area of inquiry*'. Complexity contributes in several ways to the understanding of networks. First, it shows that the structure of networks is not random but governed by general dynamical theories, namely *scale-free networks* and *small worlds* (Newman et al., 2006). Second, it establishes a link between network structure and innovation thus opening up the field of organizational design for innovation. Third, complexity theory helps make sense of the emergence of distributed and self-organizing networks for innovation and shows that these structure conjugate internal flexibility with high diversity of resources and capabilities.

Scale-free networks and small worlds

The legendary Hungarian mathematician Paul Erdos, in introducing random network theory, assumed that the structure of networks is fundamentally random: links are randomly distributed across nodes and form a bell-shaped distribution. Most nodes have a typical number of links with the frequency of remaining nodes rapidly decreasing on either side of the maximum. Watts and Strogatz (1998) showed, instead, that real networks follow the *small world* phenomenon, whereby society can be described as consisting of weakly connected clusters, each having highly interconnected members within. This structure allows cohesiveness (high clustering coefficient) and high speed/spread of information (low path length) across the whole network. Only two years later, studying the World Wide Web, Barabási and colleagues (2002) found that the structure of the Web shows a power law distribution, where most nodes have only a few links and a tiny minority – the hubs – are disproportionately very highly connected. The system is scale-free, no node can be taken to represent the scale of the system. Defined as a *scale-free network*, the distribution shows (nearly) infinite variance and (nearly) infinite or unstable mean. It turns out that most real life *small world* networks, both in the natural and social worlds, are scale-free (Ball, 2004) and fractal (Song et al., 2005). Scale-free networks appear in fields as disparate as epidemiology, metabolism of cells, Internet, and networks of sexual contacts (Liljeros, 2001).

Small world and *scale-free network* theories, along with other contributions – among the most important we cite Granovetter's *weak and strong ties* (1973, 1983) and Burt's *structural holes* theory (1992) – have opened up a new area of research and elaborated new methodological tools. The impact of these discoveries has been significant. First, the non-random structure of social networks constrains and regulates the way information and knowledge are exchanged. As innovation depends on the nature, diversity, density and amount of knowledge/information that resides, diffuses and is created within a network, it follows that by regulating information/knowledge flows, the structure of social networks affects innovation. The discovery of universal patterns governing the structure of networks helps to design networks that are more conducive to innovation (Baum et al., 2003; Verspagen and Duysters, 2003; Uzzi and Spiro, 2005; Schilling and Phelps, 2007). One could speculate that designing may aim at balancing incremental and radical innovation. Networks dominated by strong ties, through which relatively homogenous, partially redundant and often tacit information/knowledge is exchanged (Ahuja, 2000) lead predominantly to insular networks and incremental innovation. The injection of even a small percentage of weak ties lead to the transfer of non-redundant and highly diverse knowledge (Hansen, 1999), which may trigger a process of recombinant innovation with a radical nature (Hargadon, 2003). By transforming the technical and social weak ties that connect previously disjointed domains of knowledge into interfaces of the new knowledge system, a radical innovation results in the emergence of a new *small world* (Hargadon, 2003). The new interfaces of the new *small world* architecture define the interaction and nesting rules of the new system, and consequently constrain and define the interactions among different technical domains and related social and market applications (Arthur, 2009).

A new playing field for innovation

> the old industrial economy was driven by economies of scale; the new information economy is

> driven by the economics of networks. (Shapiro and Varian, 1999: 173)

Complexity theory (Kauffman, 1995, 2000, 2008; Arthur, 2009) conceptualizes innovation as an emergent property of distributed networks that develop new technologies by means of two dominant modes:

- **recombinant innovation**: recombination of existing technologies into new configurations;
- **transfer innovation or preadaptation**: discovery of new applications for existing technologies.

A large part of the literature stresses the recombinant mechanism in economics (Romer, 1994; Weitzman, 1998; Arthur, 2009), in history of technology (Mokyr, 2004), in management studies (Levinthal, 1998; Hargadon, 2003), in evolutionary biology (Kauffman, 1995; Carroll, 2006), in ecology (Ulanowicz, 2009). Recombinant innovation is defined by Nelson and Winter (1982: 130) as:

> *innovation in the economic system – and indeed the creation of any sort of novelty in art, science, or practical life – consists to substantial extent of a recombination of conceptual and physical materials that were previously in existence.*

Transfer innovation instead is based on the fact that technologies designed for a set of applications within well-defined markets are often preadapted for applications in unrelated markets (Kauffman, 2000; Dew et al., 2004; Cattani, 2005). It follows that the space of applications of any technology is open and non-predictable. Indeed, technologies purposively designed for a market can serendipitously bifurcate, sometimes giving rise to completely new markets. The non-pre-statability of the technology application space (Kauffman, 2008) transforms the closed and linear space of traditional innovation management – where new forms emerge in response to functional needs – into an *open universe* (Ulanowitz, 2009) characterized by unending technological surprises.

Both mechanisms are characterized by powerful positive feedback loops between the diversity of artifacts (with their underlying knowledge) and the diversity of application contexts to which they are exposed. Beyond a critical threshold of diversity (Kauffman, 1995), the technosphere expands with the speed of combinatorial dynamics (Weitzman, 1998), which is faster than exponential. By increasing the number of available modules for recombination/transfer and by partially decoupling the module from the function performed within the architecture, the evolution of systems towards modular architectures reinforces the feedback loops mentioned above. Moreover, the advent of the 'network society' (Castells, 2000) based on the pervasive, network-enabling information and communication technologies (ICT), has reinforced the power of the positive feedback loops associated with recombinant and transfer innovation mechanisms. In particular, the emergence of powerful modular technological platforms (such as digital computing and software) have penetrated all sectors of technologies and created a common platform for the combinatorial magic of recombinant and transfer innovation to reinforce the hybridization of the technosphere (Arthur, 2009).

These mechanisms have created a new playing field for companies (Chesbrough 2003). Innovation-based competition requires access to such a variety of knowledge assets that almost no company can individually possess (Von Hippel, 1988). Hence the need to use networks to access external resources (Powell et al., 1996; Brown and Duguid, 2000; Pyka and Saviotti, 2002; Laursen and Salter, 2006). Moreover, citation and patent research (Plerou et al., 1999; Newman, 2001; Bettencourt et al., 2007; Hung and Wang, 2010; Huang et al., 2010; see Fleming et al. (2007) for a dissenting voice) leads to the intriguing result that the architecture of technical knowledge itself is scale-free and fractal. Hence the emergence of organizational forms for innovation characterized by scale-free, small world and fractal structures can be interpreted as an Ashbian (Ashby, 1956) matching response to the increasing complexity of the technical world. This coevolution (i.e. between organizational structure and the knowledge underlying products and services – Christensen, 1997) can be seen in the biotechnology sector where the growing reliance on networks, acquisitions and alliances reflects the shift in the underlying knowledge structure the industry needs to gain. Likewise, the structure of distributed organizational forms (ecosystems) evolves to mimic the structure of interdependencies of the technosphere (Pyka and Saviotti, 2002).

The organizational response has been the development of decentralized, flexible and hybrid forms that can aggregate a diversity of resources and competences. In this new environment closed innovation models based on monolithic/proprietary networks are becoming increasingly obsolete. Open and distributed approaches to innovation in which self-organization, scale-free networks (Barabási, 2002) and 'wisdom of crowds' (Surowiecki, 2004; Page, 2008) mechanisms complement traditional hierarchies are slowly emerging.

In the quest to access and harness more diversity (Page, 2008) organizations have been trying to introduce self-organizing principles that let innovations emerge from the base of the pyramid (Gundling, 2000; Vise, 2008), and/or, break down organizational boundaries in order to hybridize the organization by co-opting external networks (Von Hippel, 1998, 2005). Open Source (OS) communities and in particular Linux is a paradigmatic case of the latter. Raymond (1999: 52) defines Linux as:

> a self organizing ecology where a collection of selfish and autonomous agents maximise their own utility. In so doing they establish a web of feedback that generates an order more elaborate and efficient than any amount of central planning could achieve.

All these principles are subjected to powerful positive feedback dynamics and are inherently scale-free, that is, similar organizing and causal mechanisms act at multiple levels of aggregation. The rise of the innovation networks that links companies, inventors, self-organizing communities, inventors and markets generates a giant technological ecosystem that thrives on combinatorial dynamics, such as the one generated by recombinant and transfer innovation mechanisms. The emergence of a globally interdependent technosphere demands innovation strategies to survive and succeed in this new interdependent space. The transformation of Procter & Gamble's innovation strategy from Research and Development to *Connect and Develop* (Huston and Sakkab, 2006) might anticipate a broader and deeper strategic change.

CONCLUSIONS

Innovation keeps the economy in a far-from-equilibrium state by renewing the set of products/services and altering/creating *small worlds* networks around emergent technologies. Following the *Long Tail* (2006) by Anderson, if one were to rank the products present at any one moment in the economy in terms of their impact or diffusion, most innovative ones would appear as minor (apparently inconsequential) events in the distribution. From there some innovations, by recombining with existing technologies, radiating into adjacent niches and transferring to new applications in unrelated markets, will grow explosively giving rise to new companies and markets. The overall result is to build new layers of technological complexity. These layers nest within existing structures and give rise to a collectively interdependent system poised at the edge of chaos. Taken in its entirety, the world of technology behaves as a giant interconnected organism that shares with the biological world fundamental evolutionary rules that govern origin, expansion, metabolism and decay of biological and technological ecosystems (Jacobs, 2000; Kauffman, 2000; Mokyr, 2004; Vermeij, 2004;

Arthur, 2009). These highlight the existence of some universal properties of the technosphere.

The technosphere is intrinsically unstable and can only exist in a far-from-equilibrium state. It develops variety and diversity at a rate compatible with the maintenance of some kind of internal coherence. Transformations seem to cluster in avalanches of change that follow a Paretian distribution and indicate a state of self-organized criticality (whereby rare events of disproportionate intensity punctuate frequent events of moderate and low intensity).

The growth of the technosphere seems to obey allometric relationships[4] described by power laws – each system with its own characteristic exponent. The technosphere escape complexity catastrophe that may follow the expansion of diversity by evolving nearly-decomposable modular architectures.

In conclusion, the world of technology is an integrated whole full of self-organizing dynamics and emergent properties. Complexity theory provides the language and an overarching framework to make sense of the organic development of the technosphere.

NOTES

1 Paul David's account of the QWERTY (1985) sub-optimal option has in fact been fiercely attacked by the defenders of the standard view of the 'survival of the fittest' hypothesis.

2 On the other side of the account are various factors which reinforce the influences which make for increasing returns. The discovery of new natural resources and of new uses for them and the growth of scientific knowledge are probably the most potent of such factors' (Young, 1928: 535).

'... Notable as has been the increase in the complexity of the apparatus of living, as shown by the increase in the variety of goods offered in consumers' markets, the increase in the diversification of intermediate products and of industries manufacturing special products or groups of products has gone even further. The successors of the early printers, it has often been observed, are not only the printers of to-day, with their own specialised establishments, but also the producers of wood pulp, of various kinds of paper, of inks and their different ingredients, of type-metal and of type, the group of industries concerned with the technical parts of the producing of illustrations, and the manufacturers of specialised tools and machines for use in printing and in these various auxiliary industries'. (Young, 1928: 536–537).

But Young's call to arms is quickly buried by the orthodoxy. Hicks wrote that increasing returns would destroy perfect competition: 'the threatened wreckage is that of the greater part of general equilibrium theory' (Hicks, 1939: 84). Sraffa also commented that increasing returns dynamics represent '...one dark spot which disturbs the harmony of the whole' (Sraffa, 1926: 536).

3 See Foster (2000) for a discussion of evolutionary theories in Schumpeter.

4 Allometric refers to a type of growth in which the parts of an organism grow at different rates determined by fixed ratios. A recent article by Bettencourt et al. (2007) finds an allometric relation between innovation and city size. I *repute* this finding extremely important as it indicates the presence of fundamental structural constraint in action. If the technosphere and biosphere follow similar principles, then the root of the allometry is in a fractal mechanism of distribution of resources (West et al., 1997).

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27

Complexity Science Contributions to the Field of Entrepreneurship

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INTRODUCTION

The fields of entrepreneurship and complexity science are linked in a number of important ways. In particular, studies of entrepreneurship and complexity science are both focused on innovation, novelty and emergence: entrepreneurship scholars study the *emergence* of new organizations, while complexity science scholars study the dynamics of *emergence* (McKelvey, 2004; Meyer et al., 2005). Additionally both fields explore interactions and emergent phenomena at multiple levels of analysis, and both highlight the importance of nonlinear and unpredictable processes that generate emergent order in dynamic systems.

For these reasons entrepreneurship has one of the most long-standing connections to complexity science as compared to other management disciplines. This connection formally began 20 years ago with Bygrave's (1989) theorizing of entrepreneurship using chaos theory (also see Bygrave and Hofer, 1991). Since then complexity science has provided useful approaches for researching emerging ventures (Stevenson and Harmeling, 1990; McKelvey, 2004), explaining start-up dynamics (Cheng and Van de Ven, 1996; Lichtenstein et al., 2006), exploring the creation of new markets and new regional economic clusters (Chiles et al., 2004; Chiles et al., 2010), and understanding the dynamics of technology innovation (Saviotti and Mani, 1998; Fleming and Sorenson, 2001).

These applications and dozens of others set the stage for the present chapter which addresses the following questions: What has complexity science contributed to our understanding of the emergence process at the heart of entrepreneurship? What more can entrepreneurship scholars learn from the sciences of complexity, i.e. how can complexity science continue to enhance our understanding of entrepreneurial action?

COMPLEXITY SCIENCE APPLIED TO THE STUDY OF ENTREPRENEURSHIP

The phenomenon of entrepreneurship

The task of defining entrepreneurship reminds me of a joke: 'What happens when you ask four Jews a question? Answer: You get at least five opinions.' Entrepreneurship involves such a range of activities and levels of analysis that no single definition is definitive. At one level entrepreneurial activity is almost always initiated by *individuals*: enterprising (teams of) actors who pursue the creation of an initiative through a dynamic process of organizing and enactment (Katz and Gartner, 1988; Gartner et al., 1992). Thus, some streams of research have explored *why* and *how* individuals choose to enact entrepreneurial organizing, focusing on the characteristics and propensities that might distinguish enterprising individuals from those who are less entrepreneurial (Brockhaus, 1980; Shaver and Scott, 1991; Baron, 1998, 2008). Scholars have also explored actor-based organizing processes including the role of intention (Bird, 1988, 1992) and action (Aldrich and Kenworthy, 1999; Baron and Markman, 2003) in the creation of new ventures.

Building on a focus of individual action is a rapidly expanding literature on *entrepreneurial opportunities* – untapped economic potential that becomes the seed and the motivation of new ventures (Ardichvili et al., 2003; McMullan et al., 2007). Opportunities – their creation, formation, discovery and exploitation – represent an intermediate level of entrepreneuring: their presence drives new venture creation, but their existence is a co-creative process involving the entrepreneur(s), the (far-from-equilibrium) market, and the resources necessary to capitalize on them (Sarasvathy, 2001; Sarasson et al., 2006). Some attempts have been made to integrate multiple elements into our understanding of opportunity recognition and creation into a single framework of entrepreneurial action (e.g. Bruyat and Julien, 2001; Chiles et al., 2007).

Third, a longstanding focus of entrepreneurial scholarship has been on the social, economic, and institutional environments in which entrepreneuring occurs. Starting with Schumpeter's seminal view on the creative destruction of entrepreneurs (Schumpeter, 1934), scholars have explored the entrepreneurial underpinnings of economic development (Leibenstein, 1967; Tan, 2007); entrepreneurial action that creates new organizational fields (Chiles et al., 2004; Maguire et al., 2004) and new markets (Sarasvathy and Dew, 2005); and institutional enablers and constraints to regional entrepreneurial development (Van de Ven, 1993; Spilling, 1996; Sorenson and Audia, 2000).

At the heart of entrepreneurship research is *emergence* – whether the creation of a venture or other organized entity through a dynamic organizing process (Gartner, 1993), or the coming-into-being of new organizational means (e.g. resources) that in turn lead to the creation of new entities, e.g. technologies, firms, networks, clusters and markets, industries, institutions. Indeed, one important focus of entrepreneurship research is the way that new ventures emerge, transform, and 're-emerge' (Gartner and Brush, 2007), and the entrepreneuring *process* has long been an important theme in the field (Bygrave, 1989; Bygrave and Hofer, 1991; Steyaert, 2007; Rindova et al., 2009). The central role of emergence is evident in studies of entrepreneurial organizing (Gartner, 1985; Brush et al., 2008), entrepreneurial networks (Singh, 1998; Obstfeld, 2005), opportunity recognition and creation (Hills et al., 1999; Chiasson and Saunders, 2005), institutional entrepreneurship (Garud et al., 2002; Lawrence et al., 2002), and in the core dynamics of organizational creation (Gartner, 1993; McKelvey, 2004; Lichtenstein et al., 2007). From this perspective, it makes sense that complexity science would provide useful models for explaining entrepreneurial emergence. To explore this connection, I begin with a brief description of emergence and place it within the context of complexity science.

COMPLEXITY SCIENCE AND ENTREPRENEURSHIP

Emergence

For over 100 years the question of 'what is emergence' has intrigued philosophers (Lewes, 1877; Popper, 1926; Stephen, 1992); evolutionists (Morgan, 1923; Kauffman, 1993); complexity scientists (Nicholis and Prigogine, 1989; Crutchfield, 1994a; Holland, 1994, 1998); and a wide range of management scholars (Weick, 1977; Goldstein, 1986, 2000; Malnight, 2001). In current social science, emergence is often defined in terms of 'qualitative novelty' – the coming into being of a qualitatively new (level of) order that is unexpected or novel in some way (Mihata, 1997). This notion is central to Schumpeter's original view of entrepreneurship, and is often used as a defining characteristic of innovation as well (e.g. Fleming and Sorenson, 2001).

For management more generally, and entrepreneurship in particular, this definition is helpfully expanded by Mihata (1997: 31) in his summary of emergence in sociology:

> The concept of emergence is most often used today to refer to the process by which patterns or global-level structures arise from interactive local-level processes. This 'structure' or 'pattern' cannot be understood or predicted from the behavior or properties of the component units alone. … In the doctrine of emergence, the combination of elements with one another brings with it something that was not there before.

Mihata's definition expands the scope of emergence, by including (a) the creation of a 'new level' of social reality, e.g. the emergence of a team, the emergence of a new venture, as well as (b) 'patterns or global-level structures' that are created in dynamic systems. These patterns may occur *within* a specific level of analysis rather than leading to the creation of a *new* level. For example in the studies of emergence based on Kauffman's *NK* fitness landscapes model (Gavetti and Levinthal, 2000; Ganco and Agarwal, 2009), what emerges is a network structure of interactions within the system that is correlated with system-level outcomes, including the adaptivity of the system overall.

This expanded notion of emergence is reflected in Goldstein's (1999: 49) parsimonious definition, which is most useful for entrepreneurship: 'Emergence … refers to the arising of novel and coherent structures, patterns, and properties in … complex systems'. Drawing on the flexibility of this definition, Lichtenstein et al. (2006: 167) define an 'emergence event' in a nascent venture as a system-wide shift that transforms the venture but doesn't result in a new level of analysis: 'An emergence event [i]s a coordinated and punctuated shift in multiple modes of entrepreneurial organizing at virtually the same time, which generates a qualitatively different state – a new identity – within a nascent venture'. This new state is not a new level of analysis, yet what emerges are new properties and characteristics that significantly affect subsequent phases of nascent organizing.

The complexity sciences of emergence

In order to appreciate how complexity science has been used to explain and understand entrepreneurship, it is important to understand complexity science itself. Like many others, my perspective is that complexity science is actually a series of sciences, each reflecting a different focal method or model or approach for exploring emergence in some way (Cohen, 1999; McKelvey, 2001). Drawing on others' maps of the field (e.g. Goldstein, 1999, 2000; McKelvey, 2004; Maguire et al., 2006) and my own analysis of complexity science in leadership (Lichtenstein, 2007), Table 27.1 summarizes 15 distinct foci of complexity sciences that have been used in management and entrepreneurship research, and how each of these has helped to explain emergence.

As Table 27.1 shows, the range of complexity science approaches applied in management and entrepreneurship research

Table 27.1 Summary of complexity science approaches for understanding emergence

Complexity science approach	*Insights into entrepreneurial processes*	*Complexity type; contribution to understanding emergence*	*References from management literature*
Deterministic chaos theory	Entrepreneurial systems are highly sensitive to initial conditions. Mathematical methods for measuring time series data reveal a range of order (i.e. types of attractors) in apparently random behavior. Shifts in attractors implies entrepreneurial learning and/or transformation.	Complexity Type II Order emergence can be measured through rigorous time series analysis.	Thietart and Forgues, 1995; Cheng and Van de Ven, 1996; Dooley and Van de Ven, 1999
Self-organized criticality	Certain dynamic systems evolve to a state in which all changes are related through a single equation, known as a power-law. Specific strategies and organizational processes can generate dynamic structuring that support innovation and creativity in organizations.	Complexity Type II Underlying causes of emergent structure can be found through repeated patterns across scales.	Morel and Ramanujam, 1999; Cederman, 2003
Fractals	Natural systems exhibit self-similarity across scales, whose dimensionality can be measured using a mathematical mapping technique. Entrepreneurial organizations may exhibit self-similar behavior and/or values across levels.	Complexity Type II Emergent order may be repeated across adjacent levels in certain systems.	Zimmerman and Hurst, 1993
Power laws	Entrepreneurial and emergence events are best captured through a Pareto distribution, not a normal distribution. That is, in contrast to traditional strategy, the most significant entrepreneurial events are found at the extremes – in the 'long tails' of the distribution, far from the mean.	Complexity Type II Emergence occurs all the time in high-frequency, low-impact events. A small number of rare events trigger whole-system transformation.	Carneiro, 1970; Stanley et al., 1996; Andriani and McKelvey, 2007
Increasing returns	In 'winner-take-all' situations, small initial differences in one entrepreneurial entity (firm, product) can generate a self-reinforcing cycle that produces non-proportional increases in overall returns.	Complexity Type II Quite different emergent outcomes may be linked to small initial differences and path dependence.	Arthur, 1990, 1994; Chiles and Meyer, 2001
Catastrophe Theory	Entrepreneurial change can be modeled such that incremental improvement across one parameter (variable) creates 'catastrophic' (punctuated) changes across another. Re-analysis of behavioral data using the higher-order polynomial models from catastrophe theory explains up to 400% more variance than the same data analyzed using linear regression models.	Complexity Types II, III Emergence often appears punctuated, even though underlying processes are incremental.	Bigelow, 1982; Gresov et al., 1993; Guastello, 1995, 1998
System dynamics	Multi-level dynamic interactions across entrepreneurial systems reflect linked feedback loops of stocks and flows. System models show how and why unexpected behavior occurs in entrepreneurial systems, thus identifying 'leverage' points for emergence and sustainability.	Complexity Types II, III Emergent (unexpected, non-linear) outcomes in dynamic systems can be discovered and generated through rigorous modeling.	Hall, 1976; Sastry, 1997; Rudolph and Repenning, 2002

Continued

Table 27.1 (*Contd.*)

Research stream	*Entrepreneurial insights from theory*	*Complexity type; emergence contribution*	*Management references*
Complex adaptive systems (CAS)	Complex entrepreneurial systems involve a set of actors or elements – 'agents' – whose interactions over time can yield emergent behavior. CAS assumes that agents follow a few 'simple rules' which yield collective behavior that is unpredictable even from a complete knowledge of every agent's capabilities and the rules they follow.	Complexity Type III Emergent outcomes are the result of 'self-organization' in complex adaptive systems.	Dooley, 1997; Choi, Dooley and Rungtusanatham, 2001
Genetic algorithms	Agents 'in silico' can be programmed to share traits, in such a way that aggregates of agents can form. Entrepreneurial emergence can be modeled as an evolutionary learning process in which qualities and skills from multiple sources lead to the emergence of new entities.	Complexity Type III Emergence involves the (re) combination of traits over time.	Krugman, 1996, Holland, 1998; Axelrod and Cohen, 2000
NK fitness landscapes	Levels of adaptability within a complex system are dependent on (1) the number *N* of nodes (agents or modules) in the system, and (2) the degree of interdependence *K* between the agents in the system. The interaction between *N* and *K* determine the ease of adaptability: the higher the interaction, the more 'rugged' the landscape, yielding more 'optimal points' of adaptation but making it harder to transition from one local optima to another.	Complexity Type III Emergent structures are interdependent with the ecology in which they are embedded	Gavetti and Levinthal, 2000; Fleming and Sorenson, 2001; Ganco and Agarwal, 2009
Agent-based simulations Multi-Agent learning models	Multiple computational algorithms, linked in a single model, generate more complex phenomena. Simulations show that adaptation and learning evolve through moves that are conditioned by agent qualities (e.g. knowledge) and local conditions (e.g. dynamism), which themselves change over time.	Complexity Types III, IV The 'rate' of emergence is increased by integrating (computational) approaches	Epstein and Axtell, 1996; Carley, 1990, 1999; Carley and Svoboda, 1996
Autogenesis/ autopoiesis	Entrepreneurial systems are self-generative and self-replicating, displaying emergent behavior. These processes originate from a 'deep structure' of rules and assumptions which lead to visible operations.	Complexity Type IV Emergence is sustainable if its system processes are self-generating.	Pantzar and Csanyi, 1991; Drazin and Sandelands, 1992
Dissipative structures	New types and levels of entrepreneurial order can emerge in disequilibrium situations, through a self-amplifying process sparked by fluctuations. Entities (groups, organizations) generate new order by dissipating large amounts of energy, information, and resources.	Complexity Type IV Emergence is a process that can be enacted (to some degree) through entrepreneurial leadership.	Lichtenstein, 2000; Chiles, Meyer and Hench, 2004; Plowman et al., 2007
Ecological systems	An ecological system reflects the essence of emergence, including high interdependence, nonlinearity, and self-organization. Entrepreneurial ecologies lead to powerful emergent effects	Complexity Type IV Emergence occurs in an ecology of resources and conditions.	Buenstorf, 2000; Colbert, 2004; Swanack, Grant and Fath, 2008

is quite broad, incorporating deterministic chaos theory and other mathematical approaches; computational modeling, e.g. *NK* landscapes and spin-glass simulations; and dissipative structures theory as well as other evolutionary frameworks. In addition, entrepreneurship and management scholars have developed purely metaphorical uses of complexity terminology, which provide an aesthetic glossary for understanding the nonlinear, unpredictable nature of emergence (e.g. Gartner, 1993) – a glossary that is not, however, without critique (Maguire and McKelvey, 1999; McKelvey, 1999a).

At the core of this critique is the issue of categorization and evaluation, i.e. how can scholars evaluate the merits of a given complexity science analysis of entrepreneurial emergence? To do so requires a meta-framework that encompasses the range of approaches from the complexity sciences – a framework that would offer a deeper understanding of what the sciences of complexity can do analytically, and how. Such a framework was initially developed by Crutchfield (1994a, b) who distinguished three different *types* of complexity science – *discovery, modeling,* and *intrinsic* complexity. In addition to those three types, a large proportion of entrepreneurial applications draw on *metaphors* from complexity science to help elucidate some of the non-mechanistic, nonlinear dynamics of entrepreneurial action. Integrating this into his analysis we can identify four types of complexity science: (Type I) *metaphorizing* complexity, (Type II) *discovering* complexity, (Type III) *modeling* complexity, and (Type IV) *generating* intrinsic complexity. These four types provide the framework within which I shall now review complexity science contributions to entrepreneurship and entrepreneurial emergence.

FOUR TYPES OF COMPLEXITY IN ENTREPRENEURSHIP

Table 27.2 provides an ordering of complexity science research in entrepreneurship, organized around these four complexity types.

Table 27.2 Entrepreneurship research across four types of complexity

Focal level of analysis[1]	*TYPE I: Complexity metaphors*	*TYPE II: Discovering complexity*	*TYPE III: Modeling complexity*	*TYPE IV: Generative complexity*
Individual	Peterson and Meckler, 2001; Groves, Vance, Choi and Mendez, 2009		Minniti, 2004	
Venture	Bouchikhi, 1993; Slevin and Covin, 1997; Hench, 1999; Fuller and Moran, 2001; Nicholls-Nixen, 2005	Bygrave and Hofer, 1991; Cheng and Van de Ven, 1996; Fuller and Warren, 2006; Lichtenstein et al., 2006; Fuller, Warren and Argyle, 2008	Lichtenstein et al., 2007; Ganco and Agarwal, 2009; Sommer, et al., 2009	Lichtenstein, 2000
Network	Biggiero, 2001			
Cluster/market		Chiles and Meyer, 2001		Chiles et al., 2004; Chiles et al, 2010
General/theory development	Smilor and Fresen, 1991; Steyaert, 2007; Schindehutte and Morris, 2009	Bygrave, 1989; Stevenson and Harmeling, 1990	Chiles et al., 2007; McKelvey, 2004	

[1] Individual works have been classified according to the most prominent focal level of analysis; most of these studies provide cross-level or multi-level analyses.

Each of the following four sections will commence with a brief description of what each type represents and the complexity streams that are represented there.

Type I – Metaphorizing complexity

Rather than being based on a particular complexity science or a method *per se, metaphorizing complexity* aims for a shift in perspective, a change in our cognitive maps, to produce a more dynamic understanding of some entity or phenomenon as a complex system. Similar to Gartner's (1993) glossary of 'emergence', this shift of perspective is expressed through specific *qualities* of dynamic systems that can be applied (metaphorically in some cases) to entrepreneurial ventures. Familiar concepts that show up in Type I Complexity include self-organization, far-from-equilibrium, nonlinear dynamics, sensitive dependence on initial conditions, and edge of chaos. Although each of these concepts has specific scientific meaning within complexity science, their use outside of that scientific context becomes metaphorical when the concepts are neither operationalized or linked to the same mechanisms or underlying drivers that give them their original rigorous scientific meaning.

In other words, Type 1– Complexity metaphors are *not* metaphors within their theoretical domain. For example, the unpredictable and cascading effects of 'nonlinear dynamics' are well understood through the complexity sciences of system dynamics (e.g. Hall, 1976), cybernetics (Marayuma, 1963), and through certain aspects of deterministic chaos theory (Bygrave, 1989); the latter science also grounds the technical construct of 'sensitive dependence on initial conditions' (Cheng and Van de Ven, 1996). However – and this is an important point – once these constructs are taken out of their broader theory, used in isolation from their nomological net and separated from their scientific and methodological grounding, they become metaphors. Equally important, metaphors in general, and complexity metaphors in particular, can be useful – even transformative (Tsoukas, 1991) – for helping us picture the world in a more holistic, dynamic, and unpredictable way. Yet, even the most artful use of metaphors should not be confused as a direct application of a complexity science *per se* (Maguire and McKelvey, 1999).

A good example of this research approach is demonstrated by Biggiero (2001), who studied how individuals can influence the 'self-organization' of a network within a specific industrial region. His analysis is based on interviews with founders and other members of a large network in Italy (of 80 firms employing 3,000 people), and draws on metaphors from fractals, cybernetics and deterministic chaos. Although this network's emergence was catalyzed by a single well-respected entrepreneur, Biggiero shows that the growth of the network – now an international center for biomedical devices – was generated through the combined interactions of hundreds of actors, as he suggests: '… the circulation of tacit and explicit knowledge among institutions, educational organizations, trade associations, firms, firm networks and single entrepreneurs'. In this way Biggiero argues that the degree of self-organization in the network depends on the level of knowledge creation and innovation within and between its members.

Fuller and Moran (2001) also use analogies from complex adaptive systems to develop an 'ontology' of small business with six emergent layers, each one transcending but including its predecessor. They reference autopoiesis to suggest that entrepreneurial emergence is '… reflexive or self-organized, a creative or generative process' (Fuller and Moran, 2001: 57). Their framework makes useful links to the concepts of adaptation, evolution, fitness and interdependency of agents (entrepreneurs, firms, clusters), providing a broad base for research in entrepreneurship.

Another study that draws on complex adaptive system analogies is Nicholls-Nixen's (2005) complexity study of entrepreneurial change.

Through interviews with founders and CEOs of high-growth SMEs she identified five 'Organizing Principles' that characterize the 'deep structure' of these firms. Her approach uses metaphors from complex adaptive systems to emphasize the importance of relationships and interactions between agents (Holland, 1988) and the role that effective leadership can play in balancing productivity and self-interest in dynamic settings (Goldstein, 1986; McKelvey and Lichtenstein, 2007).

Other papers draw on single complexity concepts to propose more parsimonious explanations of entrepreneurial phenomena. At the individual level, Groves et al. (2008) examine the claim that entrepreneurs display high degrees of 'nonlinear' thinking, which they associate with intuition, creativity, insight, and emotions. Their analysis of data from N =112 individuals shows in fact that entrepreneurs have the greatest *balance* between linear and nonlinear styles compared to accountants and professional actors. Also supporting their hypotheses, actors have higher levels of nonlinear thinking than entrepreneurs, whereas accountants have a higher level of *linear* thinking than entrepreneurs.

Nonlinearity is also a metaphor applied to new ventures by Slevin and Covin (1997), who borrow from evolutionary models of change to develop a complexity framework of new venture transitions. A core insight in their model is the suggestion that rapid transitions can minimize 'cycle times' during nonlinear shifts in the environment, leading to more effective adaptation and performance. Likewise, Peterson and Meckler (2001) argue that nonlinear and non-predictable events – i.e. 'chance' – played a role in the rise of Cuban-American entrepreneurs in Miami, Florida. Overall their analysis highlights the mix of linearity and chance in emergence of an ethnic market environment.

Separately, Smilor and Feeser (1991) explore how metaphors from deterministic chaos theory – especially 'sensitive dependence on initial conditions' – might improve our understanding of technology entrepreneurship. Steyaert (2007: 453) uses the 'attractor' construct from deterministic chaos theory to suggest that 'entrepreneuring' would make an ideal 'conceptual attractor [for the field,] around which a different terminus for entrepreneurship theory could spontaneously self-organize'.

Finally, Schindehutte and Morris (2009) utilize a host of complexity metaphors in their call for entrepreneurship researchers to harness complexity science to create a new 'paradigm' for strategic entrepreneurship. Their paper mentions metaphors from complex adaptive systems, dissipative structures, cybernetics, deterministic chaos, morphogenetic fields (cf. Sheldrake, 1981), self-organized criticality, fractals, and self-organization. The result is a '… postcybernetic, methodologically anti-reductionist paradigm … that is transdisciplinary – it integrates disciplines, and at the same time it transcends conventional disciplinary demarcations' (Schindehutte and Morris 2009: 269). Like some other metaphorical uses of complexity science, their article leaves few avenues for operationalizing concepts, making it difficult to design and conduct subsequent research that could result in cumulative knowledge.

Types II – Discovering and describing complexity

Crutchfield's (1994a) *discovering complexity* refers to a *post-hoc* analysis that measures or describes something that has emerged in a complex system, whether an emergent pattern, an emergent level of order, etc. Importantly, the discovery of order in Type II complexity is in the eye of an observer: 'Surely, the system … doesn't know its behavior is unpredictable' (Crutchfield, 1994a: 517). That is, the discovery of complexity involves a *post-hoc* analysis of time series data (e.g. system behaviors); the mathematical and conceptual tools for this analysis allow scholars to verify the existence of order emergence in dynamic systems. In Type II it is helpful to include *describing complexity,* which refers to cohesive qualitative frameworks for describing emergence in complex systems. Such descriptions, although less rigorous than the mathematical tools for *discovering complexity,* provide a systemic model that coherently explains how emergence can be studied or identified in entrepreneurial settings.

An exemplar of Type II complexity is Cheng and Van de Ven's (1996) discovery of two distinct 'epochs' – chaotic attractors – in the evolution of two high-tech innovation ventures. Previous analyses on these ventures, incorporating 96 and 152 months of event-based data, showed that their early innovation dynamics were random, unpredictable and faulty (Garud and Van de Ven, 1992; Van de Ven and Polley, 1992). This reanalysis, in contrast, utilized well-known statistical methods from deterministic chaos theory to show that these dynamics were 'chaotic', i.e. they expressed an underlying order which transcends the apparent unpredictability of the process. Further, the study confirmed the presence of a punctuated shift in the dynamics of both ventures, linking chaos theory with Prigogine's dissipative structures theory: 'Transitions between chaotic and periodic patterns of learning … can be explained by the fact that our dynamic system is a dissipative structure …' (Cheng and Van de Ven, 1996: 609). This set of tools provides a powerful approach for discerning order in complex systems.

A much more well-known instance of *discovering complexity* is the early work of Bill Bygrave, a theoretical physicist who became a successful entrepreneur and venture capitalist, and then, as entrepreneurship professor and researcher, published one of the first applications of chaos and complexity theory to management (Bygrave, 1989). He starts by advocating catastrophe theory (Thom, 1975; Bigelow, 1982) as a way to model the start-up process as '… a disjointed, discontinuous, unique event' (Bygrave, 1989: 9). Then, he explores how deterministic chaos theory could generate new insights into entrepreneurial phenomena such as flows of venture capital and the emergence of high-growth companies. Although he is skeptical about direct applications, his outlook is prescient: '[C]atastrophe and chaos provide us with useful metaphors for the entrepreneurship process [that can] help us form and sharpen our philosophy and methodology' (Bygrave, 1989: 28).

In response to this call, Stevenson and Harmeling (1990) provide an excellent foundation for *describing complexity,* arguing persuasively that complexity science could enhance entrepreneurship research methods through '… tools that illuminate the dynamism and the complexity of real organizations creating and adapting to change' (Stevenson and Harmeling 1990: 1). Taking a 'disequilibrium' approach, their recommendations for designing effective entrepreneurial research can be summarized as: incorporating reciprocal causality and nonlinear relations into rich, small-'*N*' longitudinal studies emphasizing high-quality data collection rather than the analysis of pre-fabricated data sets. More than a set of loose metaphors, their article provides a comprehensive framework for exploring and describing the complex dynamics of entrepreneurial systems.

Chiles and Meyer (2001; also see Chiles et al., 2004) make use of this framework in their analysis of emerging clusters of a specific organizational type (in this case, musical theaters) as a process of increasing returns. Supported by rich case study data on the emergence of the Branson, Missouri theater cluster, they show how the emergence of a cluster of musical theaters in the region was due to a series of nonlinear dynamics, positive feedback loops, and combinations of historical accident and dynamic interactions. Their theory focuses on the 'conditions' that lead to self-organizing processes; overall their approach leads to an interventionist model of 'stewardship' in contrast to the engineering model of 'building' an economic area.

At the organizational level, Bygrave and Hofer (1991) reframe the start-up process as a 'discontinuous change of state … [a] unique, dynamic process [that is] extremely sensitive to the initial conditions of [its] variables' (Bygrave and Hofer, 1991: 17). This is the first model to describe new venture development in terms of *cycles* of emergence and re-emergence through which entrepreneurial firms reconfigure their vision, strategy and resources to stay current with rapidly changing environments and perceptions (Brown and Eisenhardt, 1997; Nicholls-Nixen, 2005; Levie and Lichtenstein, 2010).

For example, the 're-emergence' idea is pursued in the companion studies by Fuller and Warren (2006) and Fuller et al. (2008). Through an in-depth analysis of one high-potential venture, the authors identify 'four processes of re-creating the business', i.e. four processes of (re)emergence that are based on complexity science. 'Experimentation' is similar to 'fluctuations' in dissipative structures; 'Reflexive Construction of Identity' and 'Organizing Domains' are related to the autopoiesis concept of 'deep structure' (see Csanyi and Kampis, 1985; Drazin and Sandelands, 1992); and 'Sensitivity to Conditions' is derived from deterministic chaos theory. These 'EROS' processes (Fuller and Warren, 2006) provide a complexity explanation for the drivers of growth and re-emergence in high-growth firms.

Another empirical examination of entrepreneurial re-emergence was undertaken by Lichtenstein et al. (2006), who tracked (bi-weekly for two years) the dynamics of one entrepreneur starting from the very beginning of her organizing process. Their initial analysis identified three modes of organizing: Changes in her *business vision* were analyzed through 'centering resonance analysis' that identified the entrepreneur's most salient issues; changes in her *strategic organizing* were analyzed through an event time series analysis of 'organizing moves' in the data; and changes in her *tactical organizing* were identified through a visual time series analysis of start-up behaviors. In combination they identified an 'emergence event' – distinct and punctuated shift across all three modes of organizing through which a new and more inclusive opportunity for the business *emerged,* leading to a new era of organizing for herself and her prospective clients.

Type III – Modeling complexity

Type III refers to *complexity modeling:* Agent-based systems designed to enact emergence within an 'in silico' environment (i.e. wholly developed by a human designer). Computational models and simulations allow researchers to learn how specific rules and heuristics, when operationalized as algorithms in a computer program, lead to unexpected emergence of order over time. Further, complexity modeling provides an unprecedented experimental environment in which a range of values in key variables can be tested for their influence, without interference from spurious or external effects (Davis et al., 2007). As such, complexity modeling presents a powerful context for understanding emergence, and thus, entrepreneurship (McKelvey, 2004).

An exemplar of complexity modeling is Ganco and Agarwal's (2009) study of new entrants in expanding markets, contrasting large corporations which enter through a diversification strategy with new entrepreneurial start-ups in the market. By using intra-firm complexity (K) to distinguish 'diversifying' firms from 'start-ups', they compare these two entrance strategies across a range of industry turbulence and learning capability. Their findings show that a diversifying firm's new entry leads to higher performance under conditions of greater turbulence, while independent start-ups perform better when turbulence is lower, and when the capability for industry learning is greater. Overall, 'start-ups change more frequently and face greater performance variance' (Ganco and Agarwal, 2009: 248) than diversifying corporations, but also, and unexpectedly, these new ventures perform better due to their capacity for learning.

Minniti (2004) adapted a 'spin-glass' simulation model to explore entrepreneurs' 'decision to start' that is based on two key dimensions of entrepreneurial choice (Hayak, 1952) – (1) the 'alertness' of individuals (Kirzner, 1997) and (2) the degree to which individuals are connected to each other. Results from the simulations show that 'more alert agents have higher probabilities of choosing entrepreneurship' (Minniti, 2004: 654), but that the key driver is the *inverse of* entrepreneurial networking: the less connectivity, the more the chances for unique entrepreneurial opportunities, and thus the more entrepreneurship. Further, beyond a critical threshold of new entrants, the increase in entrepreneurial activity *limits* the potential for finding unique opportunities, causing the entrepreneurship rate to decline. She concludes that 'entrepreneurial behavior and the rate of entrepreneurship may depend less on the characteristics of individuals and relatively more on the relationships between individuals' (Minniti, 2004: 656).

A different form of modeling complexity includes studies that develop formal hypotheses based on complexity science, and test them using a particular analytic model on a relatively large data set. A good example is the Lichtenstein et al. (2007) study of nascent entrepreneurship, which draws on existing theories from complexity science to define three hypotheses of new venture emergence. They then used a logistic regression model that identified emergence as the dependent variable; i.e. rather than the traditional approach of identifying the firms that 'drop out' at each stage of the analysis, the model identified the firms which stay in the pool, leading to a uniquely accurate measure of organizational emergence. Their analysis identified a generalizable pattern of temporal dynamics in the data: 'Our findings demonstrate that the ventures which emerged, compared with those that did not, pursued organizing activities at a faster rate, with lower concentration, and with timing that was later in the process' (Lichtenstein et al., 2007: 253–254).

Sommer et al. (2009) also used a combination of analytic methods in their study of learning and R&D development in high-tech start-up companies. They started by drawing on the *NK* fitness landscape model to generate hypotheses regarding whether trial-and-error learning or selectionist learning would yield higher performance across four conditions – low/high complexity of the decision environment, and low/ high levels of 'unforeseeable uncertainty' in strategic implementation. Then, using a series of self-reported measures, they analyzed $N = 58$ surveys from senior managers in young start-up firms, using traditional regression models. Their findings extends previous research by showing that, under a combination of high complexity and high unforeseeable uncertainty, selectionist learning is most effective, but only when final R&D can wait for initial feedback from the market.

Finally, I close this section with the analytical argument made by McKelvey (2004), who suggested that complexity science – 'heterogeneous agent-based computational modeling' – can make entrepreneurship research more accurate and more relevant. His essay begins with several summaries: a distinction between complexity's European school that focuses on phase transitions and dissipative structures versus its American school of computational modeling popularized at the Santa Fe Institute; a summary of Cilliers (1998) integration of postmodernism to the principles of complex adaptive systems thinking; and an epistemological argument that complexity incorporates all four of Artistotle's causes in contrast to economics' use of only *efficient* cause. With this background, McKelvey shows how complexity sciences can explain more of the complex causalities in order creation, by combining the value of rich descriptions with the generalizability of repeated modeling experiments. In this way a complexity science of entrepreneurship can 'increase scientific legitimacy and practical credibility' (McKelvey, 2004: 337).

Type IV – Generative complexity

In Type IV *generative complexity,* the order that emerges is capitalized on by the system's agents, lending additional functionality to the system (Crutchfield, 1994b: 518). Beyond a description of emergent order (Type II) and agent-based models of emergent structure (Type III), generative complexity occurs when a system agent '… has the requisite information processing capability with which to take advantage of the emergent patterns' (Crutchfield, 1994a: 518). Crutchfield labels this as 'intrinsic emergence' since the effects of order creation are discernible to agents within the system, rather than due to *post-hoc* analyses by external observers: 'In the emergence of coordinated behavior, though, there is a closure in which the patterns that emerge are important *within* the system. … Since there is no external referent for novelty or pattern, we can refer to this process as "intrinsic" emergence' (Crutchfield, 1994b: 4).

A crucial element of Type IV complexity, and the reason it is so important for entrepreneurship, is that the emergent order that emerges actually generates new capabilities and greater capacities within the system as a whole. 'What is distinctive about intrinsic emergence is that the patterns formed confer additional functionality which supports global information processing' (Crutchfield, 1994a: 518). Thus, generative complexity occurs when the emergent order extends the capability of the system – the entrepreneurial team, the new venture, the region – to create and capitalize on new opportunities, to source necessary resources, and to expand its overall potential to generate value.

One attempt to explore this process of creating capabilities was presented by Lichtenstein (2000), in his dissertation study of transformation and emergence in high-growth entrepreneurial ventures. Using the methods suggested by Stevenson and Harmeling (1990) and the lens of dissipative structures (Prigogine and Stengers, 1984), his in-depth, longitudinal tracking of four ventures identified a generalizable process of emergence involving increased dis-equilibrium organizing and increasing stress and experiments, leading to a critical threshold event, and the emergence of a new configuration, resulting in specific outcomes. The higher these outcomes – of self-reference (Smith, 1986), capacity building (Swenson, 1989), and interdependent organizing (McKelvey, 1999b) – the more likely the new venture was successful, i.e. continued to survive and grow.

A similar process of emergence and capacity creation was uncovered in the dissertation research of Chiles (Chiles et al., 2004) who pursued a 100-year study of Branson Missouri, now one of the most visited tourist areas in America. Using dissipative structures theory as a framework, their analysis reveals the process of 'punctuated emergences' in the region, each one being generated through fluctuation dynamics, positive feedback dynamics, recombination dynamics, and stabilization dynamics. Here again, the process of emergence was consistent across the four epochs of emergence in the case, and the outcomes were generative, sparking the creation of a vibrant, self-reinforcing and self-sustaining organizational community.

Chiles has taken the lead in extending this 'generative' orientation to develop a coherent complexity approach for understanding the emergence of markets, through a series of papers proposing a 'radical subjectivist' model of 'dynamic creation'. Their project begins (Chiles et al., 2007) by distinguishing Lachman's radical subjectivist [RS] approach from the classic Austrian views of Schumpeter (1934) and Kirzner (1997). They extend their theorizing by identifying three processes that generate order-creating market dynamics: empathy, modularizing, and 'self-organization' (see Chiles et al., 2010).

The latter explicitly links the radical subjectivist approach to complexity science by arguing that entrepreneurs' future expectations lead to market *divergence* – an economic process that is stronger than the *convergence* towards imitation. Divergence serves to increase heterogeneity, which pushes the market farther from equilibrium, which sparks further divergence, in a self-amplifying loop. At a critical point the market as a whole will 'self-organize', creating new regimes of order through 'punctuated dis-equilibrium'.

According to this theory, the fluctuations which drive divergence and novelty are *endogenous to the firm* – they come from the entrepreneur's imagination and foresight into how to provide 'creative value' for potential customers. When competing entrepreneurs in this far-from-equilibrium market continuously produce divergence in relation to each other, endogenous entrainment helps catalyze the self-organization of economic order: 'Thus, entrainment of entrepreneurs' activity/thought patterns in competitive entrepreneurial markets may spontaneously create a far-from-equilibrium market order that is both heterogeneous and coherent' (Chiles et al., 2010: 39). Here we have the foundations for an economic model of self-organization, an important advance to entrepreneurship and complexity science.

THE POTENTIAL OF COMPLEXITY SCIENCE FOR STUDYING ENTREPRENEURSHIP

Complexity science has generated many insights for entrepreneurship, including extensions in our research methods so as to capture the nonlinear nature of entrepreneurial action, and an expansion in our understanding of emergence, allowing us to better explain and potentially support the coming-into-being of new entrepreneurial entities (opportunities, firms, clusters, etc.). In this section I will highlight two key insights that complexity provides to entrepreneurship, namely: (1) the potential for multi-level, longitudinal, rich data research in entrepreneurship; and (2) the potential for advances from complexity science to become the basis for understanding entrepreneurship as emergence.

Complexity Science Methods for Entrepreneurship Research

A first observation is that virtually all the complexity studies in entrepreneurship include at least two levels of activity, through the integration of two more units of analysis. In fact, complexity science-inspired research seems to *require* at least two levels of activity, a clear contrast with virtually all mainstream research which is primarily single-level focused. This interaction across levels is easily seen in the empirical studies. For example, Fuller and Warren's (2006) EROS framework explains emergent properties within the entrepreneur, within new ventures, and across venture networks. Minniti's (2004) simulation models show how an individual's decision to become an entrepreneur is interdependent with their position in a network, and with the overall degree of entrepreneurship in their geographical region. Schindehutte and Morris (2009) describe the 'nexus' of individual and opportunity; Lichtenstein et al.'s (2006) study shows that the emergence of a new opportunity is reflected in shifts across three levels or contexts, of vision, strategy, and organizing. The list goes on. In particular I would note Chiles et al.'s (2004) study of field emergence, which incorporates individuals, networks, organizations, collaborations, government actions locally and at the federal level, as well as social trends including excess capital from retirees and national recognition from television and other media.

This multi-level focus is closely linked to a process-based, longitudinal view of entrepreneurship and emergence (Van de Ven, 1992).

Virtually every study mentioned takes a temporal approach, from the iterative time points of Minniti's (2004) spin glass model, to the 50+ months in the Cheng and Van de Ven (1996) time series analysis, to the 100-years of data that Chiles, Meyer and Hench analyzed (2004). The longitudinal element is at the heart of Lichtenstein et al.'s (2007) temporal study of new venture emergence; Slevin and Covin's (1997) complexity model of entrepreneurial transitions; and the conceptual frameworks of Bygrave (1989), Sarasvathy, (2001), Steyaert (2007), Chiles et al. (2007, 2010), and others. Although this temporal approach is unfortunately rare in current entrepreneurial research, scholars applying approaches from the complexity sciences seem to be leading the way.

In addition to focusing on multi-level and longitudinal studies, complexity science-inspired studies often revolve around case-study data which provides the richness necessary to capture 'the ebb and flow of top-down and bottom-up causality' (McKelvey, 2004: 330). Stevenson and Harmeling (1990) make a compelling case for the use of rich longitudinal case studies for studying entrepreneurship, and their call has been heeded by many complexity science scholars in entrepreneurship. Specifically, case studies form the core data sets for the entrepreneurial research of Lichtenstein (2000), Fuller and Moran (2001), Nicholls-Nixen (2005), Lichtenstein et al. (2006) and Fuller and Warren (2006), as well as other studies of entrepreneurial processes (e.g. Garud and Karnøe, 2003; Baker and Nelson, 2005).

These three qualities – multi-level research, temporality, and rich case-based data – are extremely rare in entrepreneurship. According to Davidsson and Wiklund's (2001) comprehensive analysis, less than 5% of entrepreneurial research is multi-level and longitudinal, qualities that they and others insist are necessary in order to gain insight into entrepreneurial process. In contrast, the core of complexity science is an exploration of the temporal, multi-level process of agent interactions, a process that can best be examined through rich case-based studies. In this way complexity science offers a leading edge approach to understanding the process of emergence at all levels of entrepreneurship.

Entrepreneurship as emergence – further advances through complexity science

An underlying theme in my review is the deep connection between emergence and entrepreneurship, and the ways that complexity science can inform both. Emergence is the creation of new 'order' – structures, processes and system-wide properties that come into being within and across system levels. Similarly, entrepreneurship is an organizing process that generates 'newness', leading to the creation of new opportunities, new products and services, new organizations, new institutions, new markets, and so on. Innovation, novelty and creative unfolding are at the heart of both fields, linking complexity science to entrepreneurship to a degree unparalleled in other areas of management research.

An examination of mainstream journals shows that these qualities of order creation and structural emergence are rarely pursued by entrepreneurial researchers. Given that emergence is purportedly central to entrepreneurship research, the dearth of studies that actually explain or track emergence is quite surprising. At the same time, with no theory of emergence and absent a specific methodological approach for identifying and measuring it, perhaps it is no wonder that so few studies explore entrepreneurial emergence. In contrast complexity science offers a powerful solution, providing the outlines of a definition and a theory of emergence (McKelvey, 2004; Lichtenstein et al., 2006), and a methodology for the collection and analysis of data that can track and explain the emergence of internal structures (Ganco and Agarwal, 2009), organizational entities

(Stevenson and Harmeling, 1990; Lichtenstein et al., 2007), and economic markets (Chiles et al., 2007, 2010).

Each of the complexity sciences has generated insights into the emergence process. Table 27.1 provides a brief summary of these contributions, and how they can expand the value and applicability of entrepreneurship research. For example, the sciences of self-organized criticality, fractals and power laws all show that emergence may be occurring across multiple levels at the same time. This insight suggests that by focusing closer on the systemic conditions of emergence, more reinforcing feedback loops may be found – and used – to identify and expand the entrepreneurial outcomes of emergence.

As another example, complexity Type III simulation studies show that emergence is an interdependent process that can be enhanced through the re-combination and integration of traits and knowledge over time. Thus, rather than focusing on how the presence of initial resources may be linked to entrepreneurial outcomes, a more productive analysis would explore how resources are interdependent with their ecology, as well as how resources can be 'acquired' and expanded through re-combination and integration of existing knowledge and skills.

A third example, based on complexity Type IV studies, involves the importance of sustainability in entrepreneurship. Specifically, models of autogenesis, dissipative structures and ecology show that emergence is viable only to the degree that system processes are self-reproducing and do not undermine or destroy the system's environment which is the source of energy for the system. This observation leads logically to a concern for incorporating a social and an environmental dimension to understandings of success, i.e. a triple bottom line as discussed below.

In sum, complexity science can be catalyst for entrepreneurship research that focuses on emergence, generating the most unique contribution that entrepreneurship can make in management. This prospect – of entrepreneurship as emergence – can be achieved with some attention to current deficits and potential next steps.

DEFICITS AND CHALLENGES – WHAT NEEDS TO BE DONE NEXT

Expanding Focal Levels of Research

Table 27.2 reveals two key deficits of complexity science research in entrepreneurship. The first involves focal levels of analysis: even though most of the complexity work involves cross-level or multi-level analyses, most studies have one focal level which is much more prominent than others. In addition, complexity researchers have emphasized just two focal levels of analysis, at the expense of research in the others. Specifically, of the 28 studies included in Table 27.2, nearly half of them focus on the venture level ($N = 13$), and another 25% focus on general advances for entrepreneurship theory and methods ($N = 7$). On the other hand, just three studies focus on individuals, another three explore the emergence of clusters/markets, and one study (3.5%) focuses on the emergence of entrepreneurial networks – a topic that should be at the cornerstone of complexity science research. Thus, our first challenge is to produce much more complexity science research on the following three levels: the individual entrepreneur, emergent networks, and the emergence of new economic clusters or markets.

Individual-level complexity research can further explore entrepreneurial decision-making processes (Minetti, 2004), as well as the entrepreneurial leadership of processes giving rise to emergence (Lichtenstein and Plowman, 2009). Boyatzis (2006) has taken a more developmental view by connecting the conditions of psychological emergence with the prospect for intentional change. His complexity science-inspired approach for developing top leaders and managers (Boyatzis, 2008) may also be usefully applied to entrepreneurial contexts.

The virtual lack of complexity research into emergent networks is curious, especially given the strategic importance of networks to entrepreneurial development (Hoang and Antoncic, 2003). As Hidalgo (this volume) shows in the chapter on networks, complexity science has a great deal to offer in this area, and these insights will surely be very useful to the theory and practice of entrepreneurship.

In terms of emergent economic clusters or markets, Chiles can be credited with leading the integration of complexity science into this arena. Starting with a study of the emergence of musical theaters in Branson, Missouri, Chiles and his colleagues (Chiles et al., 2004, 2007, 2010) have developed a comprehensive integration of Austrian economics with complexity science, providing a rigorous conceptual view of how dis-equilibrium markets self-organize, leading to entrepreneurial emergence. Given the paucity of studies of emergent markets generally (see Sarasvathy and Dew (2007), however, for a notable exception), complexity science can provide a unique and powerful approach to explaining and supporting entrepreneurial emergence.

A Complexity Science of Sustainability Entrepreneuring

An extension of this argument regards a particular focal area of research, namely sustainability entrepreneuring. In particular, the strong links between the sustainability of a venture and the sustainability of the (social) environment would imply that a good amount of complexity science research into social and environmental entrepreneurship has been accomplished. Unfortunately, aside from a research program emanating out of Adelphi University (Goldstein et al., 2008), virtually no one has yet integrated complexity thinking into social entrepreneurship generally, nor into sustainability more specifically.

The 'dynamic states' approach by Levie and Lichtenstein (2010) may offer a useful theoretical framework for this effort. They view entrepreneurial organizing as a dynamic state, which is a network of beliefs, relationships, systems and structures that convert (entrepreneurial) opportunity tension into tangible value for an organization's customers/clients, generating resources which maintain that dynamic state. In their view, the sustainability of a dynamic state is designed into its very existence, because as long as a firm is generating *value* for a target market willing to exchange resources of some sort (e.g. money, license to operate, political support, etc.) for the value generated, the firm can maintain itself over time. In this formulation, financial sustainability is integrated into the social and environmental values co-generated along with goods of economic value by the entrepreneurial firm.

Going Beyond Metaphor

Separately, the second key deficit revealed by Table 27.2 is the uneven use of the four complexity types in entrepreneurship research. Looking again at the 28 studies listed in the table, the further up the continuum from Type I to Type IV you go, the fewer and fewer studies have been done. In particular, Type I metaphors have received the most work ($N = 11$), Type II discovery and description is second ($N = 8$), Type III modeling has $N = 6$ studies, and Type IV generative complexity includes just three. Why is this the case, and why is this a potential problem?

According to Crutchfield (1994a: 526), Type IV generative complexity is the most important of the types: 'Emergence is meaningless unless it is defined within the context of processes themselves; the only well-defined notion of emergence would seem to be intrinsic emergence'. In this view, Types III and IV provide more significant insights than Types I and II.

Although I believe that emergence *is* meaningful across all types of complexity, Crutchfield's view supports the notion of a continuum of complexity, similar to Goldstein's view of a continuum of emergence (Goldstein, 2000). Essentially, Type IV and then Type III present the 'strongest' forms of complexity, whereas Type II is a relatively weaker form, and Type 1 is the most modest application of complexity science.

This framing is buttressed by claims that Types III and IV complexity are the most challenging for researchers, requiring longitudinal data and advanced methods which are very expensive to collect and pursue, and whose outcomes are highly risky. This is not to say that Cheng and Van de Ven's re-analysis of corporate entrepreneurship using deterministic chaos statistics was easy! However, merely borrowing metaphors from a variety of complexity sciences will not lead to the development of a comprehensive theory of emergence which can be then tested with longitudinal, case-based data, as is possible with studies using Type III and Type IV complexity. Thus, I argue that we have reached the point of quickly diminishing returns to metaphorizing complexity, Instead, the field of entrepreneurship is entering an era of rigorous theoretical explorations and computational experiments which can identify and generate emergence in entrepreneurial contexts. Given its 'firm foundations' (Maguire and McKelvey, 1999) in complexity science, such work is likely to produce generalizable insights into the emergence process, and to make significant contributions to understanding entrepreneurship.

CONCLUSION

Overall, the application of complexity sciences has benefited the study of entrepreneurship. Because both fields focus on the phenomenon of emergence, it is not surprising that applications of concepts from complexity science to entrepreneurial thinking were prominent a full decade before the *Organization Science* special issue on complexity in management more generally.

My introduction of four types of complexity has two aims, in addition to being perhaps a more interesting approach than the more common levels of analysis model. First, as I've mentioned, the framework suggests directions for further research, away from informal metaphors and toward rigorous models and disequilibrium approaches that can *generate* emergence, as much as explain it. This direction would represent a maturing of the field, which, after 20 years of complexity applications in entrepreneurship, seems to be timely and appropriate. A second aim is to introduce this framework into organization science more generally. Although there has been good progress in applying complexity science to management and organizations, a situation to which this volume is testament, there is lots of scope for additional rigorous and thoughtful research. The four-type complexity framework can encourage and organize this rigor and thoughtfulness.

In both cases I am making a broader claim which is well-expressed in the summary of 15 complexity science approaches contained in Table 27.1. Complexity science is – and should be – much more than a set of computational approaches. For example, *NK* fitness landscape models may be effective at highlighting some dynamics of interaction and emergent structures, but they by no means address the most paradigmatic type of complexity. Foss and Ishikawa (2007) make this argument, and in a much stronger manner, by criticizing complexity science-inspired analyses of rugged fitness landscapes that are devoid of imaginative, forward-thinking entrepreneurial agency. On the other hand, emergence as a dynamic, system creating process is quite evident in other Type III and Type IV complexity models, which can provide a more nuanced and applicable understanding of entrepreneurial behavior.

Overall, my analysis reflects a view of entrepreneurship as emergence: the study of entrepreneurship is the exploration of emergence, including its processes, dynamics and outcomes (e.g. McKelvey, 2004). This view implies a broader set of boundaries for defining the entrepreneuring process. Moreover – and more radically – it provides a strong rationale for entrepreneurship scholars to more fully 'embrace' the concept of emergence as central to their goals. Recently, it has been suggested that the field of strategic management has "co-opted" entrepreneurship (Baker and Pollock, 2007), but the application of complexity science approaches and insights to understanding entrepreneurship as emergence may provide an important point of leverage for renewing entrepreneurship as a distinct and theory-driven field (McKelvey, 2004).

In closing, I remain inspired by Stevenson and Harmeling's (1990) recognition of the power and unpredictability of a 'chaotic entrepreneurial theory'. Challenging though it is to incorporate complexity science into our work, the effort promises to yield significant contributions to theory. Additionally, these authors provide a kind of manifesto for all of us seeking to integrate complexity science into *relevant* research (Stevenson and Harmeling, 1990: 13):

> If we are so tame as to only report that which can be proved beyond a shadow of a referee's doubt, it is unlikely that we will be of significant help to those managers who are leading the way. … We can either rest on our laurels and rely on theories that anesthetize us with their elegant simplicity or we can seek to become more thoughtful and scientific in our approach to the study of management and organizations.

May we continue to be thoughtful and rigorous in our application of complexity science to the study of entrepreneurship, management and organizations.

NOTE

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28

Complexity and Competitive Advantage

Oliver Baumann and Nicolaj Siggelkow

INTRODUCTION

The notion that firms face many complex challenges – both intra-organizational and with regard to their competitive environment – is a commonplace in the strategy field. At the same time, though, the connection between complexity and the main issue of strategic management – how to gain and sustain competitive advantage – is still not well understood. Is complexity detrimental to this quest, or can it also convey advantages to a firm? What is the role of organizational design in this context: are particular structures better suited for coordination in complex environments than others? And how do the strategies employed by a firm's decision makers to deal with complexity affect organizational performance? This chapter provides a review and assessment of the literature that has evolved around these questions.

The starting point of most of this work (as of this review) is Simon's (1962: 468) seminal article on the architecture of complexity: '[B]y a complex system, I mean one made up of a large number of parts that have many interactions. […] in such systems the whole is more than the sum of the parts in the weak but important pragmatic sense that, given the properties of the parts and the laws of their interaction, it is not a trivial matter to infer the properties of the whole.' Clearly, this definition of complex systems can be applied to organizational systems as well, like, for instance, in Thompson's (1967: 6) work on organizational design: '[T]he complex organization is a set of interdependent parts which together make up a whole in that each contributes something and receives something from the whole, which in turn is interdependent with some larger environment'.

In short, the central tenet of the above perspective states that *interdependencies* between intra- and extra-organizational elements denote the main driver of organizational complexity. Yet as Simon (1962) already indicated, the question of how exactly the behavior and performance of an organization emerges from the interaction of its parts – among themselves and with the firm's environment – is a hard one to tackle, in particular using 'standard' approaches of social science research. In recent years, however, this objective has received renewed attention as computational models from research on complex adaptive systems, set initially in the physical and biological sciences, have been transferred to the management sciences. The general approach of these models can be summarized as follows: Organizations are seen as sets of interdependent activity choices. Individual agents (e.g. firms or managers) are endowed with capabilities to search and make decisions (typically assuming bounded rationality) with respect to these activities. The agents are connected in various ways (e.g. reflecting the task environment or the organizational structure) and, by acting within their individual purview, are collectively arriving at a 'solution', a set of choices for the various activities. In a sense, the agents are trying to solve a high-dimensional problem.

This explicit treatment of organizations as complex adaptive systems conveys an important advantage: 'By not forcing scholars to understand all the parts of a complex system in a holistic way, [complex adaptive systems] allow investigators to focus on an agent in its local environment' (Anderson, 1999: 220). Hence, there is no need for any top-down functional specification of a system's behavior. Instead, a modeler only needs to be concerned with the elements that comprise the system, with the ways by which they are interdependent, and with the agents' local behavior. The global, system-level behavior, in contrast, is left to emerge bottom-up. Using simulation experiments to rigorously explore these emergent properties by systematically altering the model parameters, a substantial body of research has uncovered mechanisms and conditions that shed light on the role of interdependencies for competitive advantage.

In the following section, we review this literature with regard to two major implications for competitive strategy: (1) creating barriers to imitation and (2) requiring firms to balance search and stability. The third section assesses the current status of this body of research and, in particular, its shortcomings. The final section points to possible directions for future research at the intersection of complexity and competitive advantage.

IMPLICATIONS OF INTERDEPENDENCIES FOR COMPETITIVE ADVANTAGE

Creating barriers to imitation

The notion that a firm's activities are highly interdependent and therefore need to fit together to yield high performance, is a long-standing concept in the strategy field (Chandler, 1962; Khandwalla, 1973; Drazin and Van De Ven, 1985; Porter, 1996). For instance, a firm's management team faces decisions about how to procure, design, finance, manufacture, etc., many of which are interrelated. For the management team, the presence of interdependencies creates trade-offs across choices, making the firm's strategizing efforts – the search for a combination of choices that, together, creates high performance (Rivkin and Siggelkow, 2006) – highly difficult. For example, a firm may only gain a benefit from increasing product variety if it also increases the flexibility of its manufacturing system, provides additional training to its sales force, and enhances its logistics processes. At the same time, the fact that practices often come in bundles can also convey an advantage to a firm that has managed to identify a high-performing set of activity choices. Because the advantage for the firm stems from the set of interdependent activities rather than from any individual choice, this systemic property may be hard to imitate by competitors.

The above notion is reflected in different streams of research. One is grounded in the theoretical and empirical treatments in the economics literature that have been concerned with exploiting complementarities among activities (Milgrom and Roberts, 1995). Using the introduction of flexible manufacturing systems as a motivating set-up, Milgrom and Roberts (1990) observe that 'successful moves toward "the factory of the future" are not a matter of small adjustments made independently at each of several margins, but rather have involved substantial and closely coordinated changes in a whole range of the firm's activities' (p. 513). Likewise, they also suggest why successful bundles of practices often diffuse rather slowly, if at all, across the competitive landscape. They argue as follows: In interdependent activity systems, benefits tend to arise only if all necessary dimensions across which complementarities operate are changed in a coordinated fashion. Changing only a few of the dimensions typically conveys only a small or even a negative payoff. Instead, major coordinated efforts may be necessary to move a system from one configuration to another. They illustrate this barrier to diffusion with the case of 'modern (lean) manufacturing' which would require changes of a number of system elements for firms engaged in traditional mass manufacturing. In adopting these new practices, many firms did not understand or consider the full system of interdependencies, making costly (negative) experiences by adapting only some of the necessary activities. Subsequently, a number of qualitative and quantitative studies of industries and individual firms (e.g. Milgrom and Roberts, 1995; Porter, 1996; Ichniowski and Shaw, 1997; Ichniowski and Shaw, 1999; Whittington et al., 1999; Siggelkow, 2001) have supported the imitation-deterring aspect of a successful set of interdependent practices that requires an imitator to make a number of simultaneous modifications to its activities rather than incremental changes alone. For instance, Porter (1996) illustrates how the various choices made by Southwest Airlines are reinforcing each other, creating one large consistent 'activity system'. Attempts by practically all incumbent carriers (for instance, Continental with Continental Lite, United with Ted, Delta with Song, KLM with Buzz, British Airways with Go) to create subsidiaries that would copy Southwest Airlines activities have failed. Given the tradeoffs that Southwest's activity choices created vis-à-vis the existing activities of the incumbent carriers, the incumbents were unable (and unwilling) to copy Southwest's entire activity system. Yet, due to its interdependent nature, partial imitation of Southwest's activity system did not yield partial benefit … it only created chaos.

Building and extending theoretical work on complementarities among activities, a number of simulation studies have relied on Kauffman's *NK* model (Kauffman, 1993, 1995) to deal with the issue of imitating successful bundles of practices between competitors. The *NK* model allows researchers to create settings in which *N* decisions that a firm has to resolve are interdependent to varying degrees. In particular, each decision is assumed to be affected by *K* other decisions. Given these features, the *NK* model has proved to be a convenient set-up to study the effect of complexity on various strategic issues. Rivkin (2000), for example, shows that the global optimization of a successful strategy, i.e. any optimal algorithmic imitation of a set of interdependent decisions, becomes intractable under the following conditions: when the degree of interdependence is modest to high, when strategies consist of a sufficiently large number of decisions, and when the time involved in each algorithmic step is not trivial. He goes on to argue that if, more behaviorally realistic, firms do not optimize but instead imitate a successful strategy by incremental improvement, they are highly unlikely to eventually find the global optimum. Instead, most firms get stranded far away from the best strategy, i.e. on a different but less optimal set of internally consistent choices that cannot be further improved through incremental change. Likewise, follow-the-leader type imitation efforts – recreating the strategy of a high-performing rival as much as possible yet imperfectly – does not pay off in the face of complexity: 'In a strategy whose pieces are numerous and tightly knit, small probabilities that each element will be replicated incorrectly cumulate to produce a high likelihood that imitators will fare poorly' (Rivkin, 2000: 839). To summarize, assuming that managers' understanding of their rivals and their replication capabilities are imperfect, a complex strategy can protect a firm against imitation.

In related work, Rivkin (2001) extends these findings to the case in which a firm wants to deter imitation efforts but at the same time needs to replicate a successful strategy for its own purposes. This objective poses a trade-off: While simple strategies can easily be replicated by a firm, they can also be easily imitated by competitors. Yet conversely, very complex strategies resist replication and imitation equally. The main finding of Rivkin's (2001) analysis is that moderately complex strategies bear the greatest relative advantage as they are more easily replicated than imitated. This is documented for different set-ups. The first one refers to the situation in which both the replicator and the imitator can (re)discover the best solution only by incremental search, and the replicator is at an advantage because it can start the search closer to the benchmark solution. While for low levels of complexity, both the replicator and the imitator will – through a sequence of incremental performance-enhancing steps – eventually find very good solutions, both types of firms are likely to get stranded on a different but lower-performing local optimum when the strategy is highly complex. For moderate levels of complexity, in contrast, the replicator can exploit its superior starting position, while the imitator will founder more quickly due to its worse starting conditions. Furthermore, the better the replicator can reproduce a successful template, the more complex the underlying set of decisions can be in order to deter imitators without hurting the replicator as well. Similar results can be observed for follow-the-leader type imitation behavior. Here, the replicator has an advantage over the imitator, as this firm is more likely to know which decisions are already aligned with the template and which it should continue to copy. For the same reasons as above, this advantage is of little value for strategies with very low or very high levels of complexity, but pays off the most for moderately complex strategies. In sum, Rivkin (2001) shows that in situations of imperfect information about successful strategies, a firm's relative advantage over its competitors is greatest for moderate levels of complexity. Because the firm has a better understanding of the strategy, it is able to rather accurately replicate it and at the same time ensure that imitation efforts are much less fruitful.

More recently, Csaszar and Siggelkow (2010) take the perspective of the copycat to study the conditions in which it is advisable to engage in small, intermediate, or large imitation attempts, taking into account not only interdependencies between practices, but also the time horizon and the similarity between firms. They show that if short run considerations predominate, such as, for instance, in fast-changing environments, firms are best off – independent of the degree of complexity – when they engage in large-scale imitation efforts. If they are unable to do so, they should copy only a small set of choices that does not disrupt too many practices and that allows the firms to recover quickly if needed. If, in contrast, an intermediate number of practices is copied, chances are high that the imported practices are incompatible with the rest of the firm's practices, and firms are unlikely to quickly recover from this setback. What is worst for short time horizons, however, proves to be the best imitation strategy in the long run: copying an intermediate range of practices. Especially in the presence of many interdependencies, broad exploration is often required to ensure a firm's well-being in the long term. A strategy of copying an intermediate range of practices supports this objective by helping a firm escape from its current configuration and trigger further improvement efforts, while at the same time not locking the firm in too quickly on the currently (but maybe not globally) best industry practices. Only under conditions of low complexity is it helpful to try to copy as much as possible. As Csaszar and Siggelkow (2010) continue to demonstrate, imitating the configuration of shared practices from dissimilar firms (i.e. firms that operate in different environments) leads to very different recommendations. They find that in turbulent environments (in the short run) and independent from the degree of complexity, firms should avoid any imitation attempts. This is due to the fact that imitated practices are likely to interact with practices that are not shared, and will thus create misfits with the copycat's unique set of practices. Furthermore, in stable environments (in the long run), firms should at best engage in small, random imitations that may dislodge them from a local peak and induce further exploration. In sum, the findings point to the difficulty of 'getting it right' when imitating successful practices, and to the non-trivial interaction of complexity, similarity between firms, and time considerations in determining the most effective strategy for a copycat. More importantly, their findings show that despite the fact that complexity harms the ability to imitate, it only plays a role under specific conditions in affecting a firm's decision to engage in imitation efforts.

Requiring a balance of search and stability

While focusing on the barriers to imitation that successful bundles of interdependent activity choices may help erect, we have so far ignored the question: How do firms identify such successful bundles in the first place? As we have implicitly indicated in our review of research on imitation efforts, this objective constitutes a significant challenge in the presence of interdependencies. Underlying this challenge is the fact that interdependencies between practices create numerous local optima, i.e. bundles of practices that are internally consistent but that cannot be further improved by adapting only one or a few individual practices. Instead, a major coordinated effort is required to 'move' an organizational system from the proximity (out of the basin of attraction) of one local optimum towards that of a higher-performing one. However, due to bounded rationality (Simon, 1955, 1956) and because strategy problems are computationally complex (Rivkin, 2000), decision makers cannot simply optimize and then implement the solution that denotes the global optimum (Simon, 1962). Instead, decision makers have to search adaptively for sufficiently good solutions (March and Simon, 1958; Cyert and March, 1963; Nelson and Winter, 1982).

It has become an established notion in the strategy literature that in order to deal effectively with this challenge, firms need to balance search and stability (Levinthal, 1997; Rivkin and Siggelkow, 2003). On the one hand, firms need to engage in search – by generating and evaluating alternative configurations of activity choices – to continue exploring alternative (and potentially superior) strategies and maintain their ability to adapt. On the other hand, firms also need to stick with good solutions once they have identified them, rather than wandering off. This becomes necessary due to the high risk of cycling endlessly: In the presence of interdependencies, any uncoordinated adaptation of individual practices, though possibly beneficial in a local context, may affect firm performance in negative ways. It will, in turn, thus trigger further adaptation efforts which may result in a repetition of the same cycle or a similar one. In the following, we focus on work that has studied how a firm's effectiveness in balancing search and stability may be affected by the design of the organization and by the search strategies that its decision makers employ.

The role of organizational design

The notion that the right way to organize depends on the presence of interdependencies goes back to early research by organizational theorists that have identified complexity as a key contingency in their quest to define a mapping between a firm's environment and its optimal design (Thompson, 1967; Galbraith, 1973; Khandwalla, 1977). In recent years, simulation modeling has provided the methodological apparatus to delve more deeply into the role of organizational design in the face of interdependencies between organizational activities. We suggest that existing work along these lines can be broadly classified by its focus of analysis: (1) individual design elements and (2) entire organizational structures.

Representing the first set of studies, Rivkin and Siggelkow (2003), for instance, show that interdependencies among elements of organizational design – a well-established concept of organizational design (Khandwalla, 1973; Mintzberg, 1979) – may arise because they affect both how broadly a firm searches for good sets of choices and whether the firm is able to stabilize around those sets once it has discovered them. Put differently, '[o]ften, a firm that adopts an element that pushes it toward broad search benefits from a second element that pulls it toward stability' (Rivkin and Siggelkow, 2003: 291), and vice versa. In particular, the authors study the implications of three major variables of organizational design: the decomposition of an organization's decision into departments, a vertical hierarchy, and an incentive system that rewards subordinates for departmental or firm-wide performance. For instance, they show that consistent with conventional wisdom and prior qualitative research, an active vertical hierarchy (a CEO that reviews proposals that get sent up from subordinates) is particularly helpful when interactions among decisions are pervasive. Under these conditions, the active hierarchy provides stability by ensuring that proposals from different departments will only be implemented if they have high fit from a firm-level point of view. For this design element to provide a benefit, however, the information flow in the hierarchy must be rich in order to make sure that the second major challenge – broad search – finds consideration as well. Otherwise, an active hierarchy can lock a firm in on suboptimal solutions prematurely and even lead to worse performance than if the CEO were purely passive and simply accepted each proposal that got sent up.

In related work, Siggelkow and Rivkin (2005) extend this analysis by studying a number of organizational archetypes that vary in how much power they grant to department heads (ranging from a decentralized archetype with full autonomy on the side of the department heads, to an archetype in which department heads have no power at all and a central authority provides coordination). The different archetypes again consist of a number of finer-grained design elements. Siggelkow and Rivkin (2005) then focus on how the value of these different designs depends on the complexity and turbulence of the environment. The underlying argument of their paper is that in turbulent settings, designers should emphasize elements that allow firms to improve their performance speedily – by emphasizing stability rather than broad search, whereas in complex environments, choosing a design that induces a firm to search broadly becomes paramount. In environments that are both complex and turbulent, finally, organizational design should help strike a balance between search and stability. The results of the simulation model employed by Siggelkow and Rivkin (2005) indicate that different elements of organizational design affect the speed of improvement and the diversity of search in different ways, depending on the archetypes they are embedded in. Only few design elements such as rewarding low-level managers for firm-wide performance to boost the speed of improvement, prove beneficial for a particular purpose independent of the archetype in which they are embedded. The effects of most design elements, in contrast, tend to be strongly contingent.

Focusing on entire organizational structures rather than individual design elements, a second set of studies has put forward a different mechanism through which organizational design may affect the balance between search and stability. Siggelkow and Levinthal (2003), for instance, investigate the temporary succession of different organizational structures and its performance implications. In particular, they study how different generic designs – a centralized structure, a decentralized structure, and a temporarily decentralized structure that is later re-integrated – may help a firm explore and adapt after an environmental shock has occurred. They find that in complex environments, temporary decentralization yields the highest long-run performance. This benefit arises as a temporary separation – even if interdependencies remain between the different departments – is beneficial because it will induce overall broader search on the level of the organization. However, to reap this benefit of broader search, the firm must eventually re-integrate in order to coordinate across the different departments, thus providing stability.

Siggelkow and Levinthal (2005) have extended this argument to study when transitions between a broader range of organizational structures are beneficial even in stable environments. They demonstrate that different organizational structures differ in their sticking points, i.e. in the set of configurations at which a firm that possesses the respective structure will stop searching as it cannot identify any alternatives that would be approved by all relevant decision makers within the firm. The paper shows that if a firm has stopped searching given its current structure, a shift in structure may induce further search and allow the firm to identify higher-performing sets of activity choices. (For a case study, of a firm oscillating between forms that create more exploration and more exploitation, see Thomas et al. (2005).)

The role of decision makers

Apart from organizational design, a firm's effectiveness in addressing complex strategic challenges is affected by the search strategies that its decision makers apply. In this context, the work reviewed below has uncovered two broad classes of mechanisms that affect the balance between search and stability: (1) managerial cognition (e.g. 'maps' or analogies) prior to a search process that dampen some of the implications of bounded rationality by allowing a firm to start its search for good solutions at above-average alternatives; and (2) other characteristics of boundedly rational decision making (e.g. imperfect evaluation skills or a 'preferred direction' for search) that may help overcome local search by causing perturbations and introducing unintentional but helpful 'detours'.

Starting with research that falls into the first category, Gavetti and Levinthal (2000) study how cognitive maps, lower-dimensional representations of the actual strategic landscape (i.e. the relevant variables and their interdependencies), affect the dynamics of search. Cognitive maps such as particular strategy frameworks allow evaluating broad and potentially highly different alternative courses of action in an offline manner, i.e. by means of theoretical reasoning and without the risk of having to implement a particular alternative to learn about its value. The authors argue that such maps, even if they are crude and only roughly capture the real structure of the environment, can be valuable to guide the initial search efforts and likewise constrain the direction of further search, thereby providing stability, in particular in complex environments. Likewise, changing one's cognitive representation can be a helpful means of adaptation in order to direct attention to different aspects of the competitive landscape and open up further improvement potential, even in static worlds. Such shifts, however, also involve a trade-off as they imply a loss of tacit knowledge associated with the prior cognition that may lead to a higher risk of organizational mortality. Overall, the study starts treading a middle ground with regard to the implications of bounded rationality for solving complex strategy problems that lies between the highly constrained notion of experiential local search on the one hand, and the highly unrealistic assumptions of (cognitive) optimization under constraints on the other. In Gavetti and Levinthal's (2000) world, decision makers cannot envision the full set of alternatives available to them. They may, however, act intendedly rational and affect their effectiveness in dealing with complexity by how well they form simplified cognitive theories of the world, before continuing to flesh them out through experiential search.

A similar mechanism is portrayed in Gavetti et al. (2005). This study investigates the value of analogical reasoning for strategizing in novel and complex worlds. The starting point is the question: How do firms create a competitive position in an unfamiliar industry? This poses a significant managerial challenge because cognitive maps that are founded on experience are often not available in highly novel environments. However, decision makers may be able to transfer wisdom from similar settings to a new one by generalizing from prior settings to the current environment. In Gavetti et al. (2005), managers form representations about the strategic interdependencies in their industries that drive the relation between firm action and performance, defining characteristics that distinguish between similar and different industries. Such classification can allow managers to identify similar industries and transfer similarities between settings to a new setting, thus guiding their firms' search in the novel industry by providing them with good candidate solutions. The results of this study suggest that analogical reasoning is most powerful when managers can form accurate classifications and when they have broad experience, which proves to be more important than the actual depth of experience. Furthermore, the results show that applying an analogy in too orthodox a manner, i.e. constraining search strictly to what the analogy suggests, can be dysfunctional when the quality of a firm's representation is poor. Heterodox firms, in contrast, by not holding on to (bad) analogies too firmly, do not pay the same price, suggesting that the value of analogies lies more in seeding good starting points for further search efforts rather than as a means to constrain them. To sum up, Gavetti et al. (2005) give another account for when and how managerial cognition – managers that act intendedly rational, although the complexity of the environment exceeds their information processing power – can be a valuable response to the demand for search and stability in complex and novel worlds.

Other research on the role of a firm's decision makers in dealing with complex strategy problems falls into our second category. In this context, for instance, Knudsen and Levinthal (2007) study how imperfections in evaluating alternative courses of actions – affecting an aspect of problem-solving search that has only been implicitly considered in prior research – the dynamics of search and stability. In particular, they study the implications of two types of imperfections: type I errors of rejecting a superior alternative, and type II errors of accepting an inferior solution. Based on this evaluation structure, they focus on a collection of decision makers and superimpose an organizational structure, ranging from a centralized decision-making structure (hierarchies) on the one hand, to decentralized structures (polyarchies) on the other. Their main result is that a moderately imperfect evaluation of alternatives can be valuable. While perfect evaluation skills create a fast search process as only performance-increasing alternatives are accepted, imperfect evaluators can reach higher performance, which is particularly helpful under conditions of complexity. This result arises because the (unintentional) implementation of (some) performance-decreasing alternatives may temporarily lead a firm 'downward', but can help it escape the proximity of a lower-performing local optimum and move into the proximity of superior solutions. In this sense, the results of Knudsen and Levinthal (2007) also have implications for the design of organizations as discussed in the previous section: 'The less able (or, conversely, the more able) individual evaluators are, the more attractive are organizational forms that tend toward hierarchy (polyarchy) as the hierarchical structure tends to compensate for the high error rates of less able individual evaluators (or, conversely, the variance induced by the polyarchy forms tends to compensate for the overly precise judgments of more able evaluators)' (Knudsen and Levinthal, 2007: 41).

A related effect has also been uncovered by Winter et al. (2007) in their treatment of a firm's 'obsession' with a 'preferred direction' and its implications on the dynamics of search. In their conceptualization, a 'preferred direction' can be given a variety of interpretations, ranging from foresight or causal understanding to irrational obsession. They argue that in a process of local search, an intermediate weight on non-local considerations, i.e. 'moderate obsession', is particularly valuable in the presence of complexity. Similar to the above case of imperfect evaluation, such non-local influences may convince a firm to implement alternatives that denote a (temporary) setback as compared to its status quo solution. In inducing this behavior, however, the pitfalls of local search in the presence of interdependence – the quick stranding on a low-performing local optimum and a premature end of the search process – can be overcome. At the same time, the moderate weight on non-local influences helps find a balance between search and stability and thus avoid that the search leads to an aimless drift across the space of alternatives.

ASSESSMENT OF THE FIELD

To be clear, the above review has only dealt with a fraction of research at the intersection of complexity and competitive advantage. In particular, we have been concerned with agent-based modeling studies that have probed into the strategic challenges posed by interdependencies between practices. Critically taking stock of this body of research, as well as the field more broadly, we believe it is fair to state that the research up to now has been both fairly fragmented and somewhat disconnected from mainstream strategy research. We elaborate on each argument in the following.

With the exception of the work on complementarities (Milgrom and Roberts, 1990; Milgrom and Roberts, 1995) and the last paper (Winter et al., 2007), the above review has been largely concerned with studies that have referred to Kauffman's *NK* model (Kauffman, 1993, 1995). This model – originally developed in evolutionary biology – has been fruitfully applied to tackle a number of issues in the management sciences in recent years (see, e.g. Porter and Siggelkow, 2008, for a review). It is particularly well-suited to create – in a simple stochastic but well-controlled manner – complex problem structures that serve to represent a number of elements (e.g. organizational activities). However, besides the *NK* model, a number of other canonical models have been developed and put to use, such as, for instance, March's model of exploration and exploitation (March, 1991), system dynamics models (Sterman, 2000; Sterman et al., 2007), multi-armed bandits (Sutton and Barto, 1998), genetic algorithms (Bruderer and Singh, 1996), or cellular automata (Lomi and Larsen, 2001). While all of these models have been applied to conceptualize firms as complex adaptive systems, or to study the intra- and inter-organizational implications of complexity for strategy issues, each model has taken a different approach and generated a somewhat separate stream of subsequent work. Given the potential overlap between these different approaches, a fruitful avenue for future research might be to examine the same set of issues with a range of different models.

The second observation is that most of the work that has addressed the interrelationship of complexity and competitive advantage has referred to computational models, whereas quantitative or qualitative empirical work has remained rather sparse (exceptions include, e.g. Fleming and Sorenson, 2001; Siggelkow, 2002; Fleming and Sorenson, 2004; Fleming et al., 2006). Likewise, empirical work has only been rarely used to inform the particular modeling set-up. (For one attempt to let empirical work on interdependencies inform the modeling structure within the *NK* framework, see Rivkin and Siggelkow (2007).) Clearly, the focus on computational research has a number of advantages: It allows modeling and analyzing complex adaptive systems at a level of detail that would be hard or impossible to keep tractable with standard mathematical techniques. At the same time, it offers a virtual laboratory that allows conducting experiments and generating data at a level of detail that may be hard to obtain using an empirical approach. In contrast, the bulk of research on competitive advantage typically comes in an empirical or a game-theoretic flavor. Due to the little cross-fertilization that is going on between mainstream strategy research and research based on computational models, the latter domain may run the risk of being pushed into a marginal niche, if this situation remains unchanged.

In sum, for the field to progress further, and to persistently move along the path from 'fad to firm foundations' (Maguire and McKelvey, 1999), it appears to be necessary to stress the connecting links and integration potential across two levels: one relates to the phenomena currently examined, and to the various models used to do so; the other refers to the current emphasis on simulation modeling and its relation with other methodological approaches to management research. In the following section, we outline a number of issues that, we believe, could be first steps for moving the field into this direction and for future fruitful research opportunities, more generally.

FUTURE DIRECTIONS

To further advance our understanding of the interrelationship between complexity and competitive advantage, a number of potential directions might be pursued that address the two shortcomings identified in the above assessment.

One is to include in simulation models features that connect them with other, mainstay strategy models. For instance, one desirable extension would be to study competitive dynamics by modeling more interaction among firms. Currently, competition among firms is typically absent (see, e.g. Lenox et al., 2006, for an exception that couples an *NK* model to a standard IO model). One might conceive of firms as being arrayed on a two-dimensional grid, letting each firm interact with its neighbor – an approach that has been used in similar and other contexts by researchers that have applied cellular automata (Lomi and Larsen, 1996; Wolfram, 2002). Alternatively, as firms move closer to each other on a commonly shared performance landscape, they might 'deform' the landscape, representing competitive interaction.

A second avenue would be a richer modeling of decision makers. As we have indicated in our review of prior work, current research is increasingly starting to tread a middle ground in the representation of the notion of bounded rationality as intendedly rational behavior by agents with (severely) limited information processing power. Moving further along these lines might include different aspects of forward-looking behavior (besides cognitive maps or analogies) such as memory and the formation and adaptation of theories about the search space a decision maker is traversing (Nelson, 2008). Likewise, a richer modeling of knowledge structures within firms (Ren et al., 2006) could potentially yield a new set of insights.

A third path forward would relate to making exogenous variables endogenous. Currently, most features of the models – the complexity or turbulence of the environment, or the search and change behavior of the decision makers, to name but a few – are directly controlled by the modeler. Endogenizing some of these variables – e.g. turbulence that occurs when one firm has identified an outstanding new strategy or firms that adapt their search efforts based on their performance relative to their aspiration level (which, in turn, might endogenously result from their current understanding of the profitability of the industry they are in) – might create interesting dynamics and yield new insights. (For a first attempt to endogenize the choice of organizational structure, see Siggelkow and Rivkin (2009).)

Another important future direction is to engage in empirical work that draws on the theoretical insights generated by the simulation work. Theoretical modeling has in some sense outpaced empirical research on the topics of this chapter. To separate solid from less solid claims, it would be extremely helpful to empirically test hypotheses that simulation-based research has generated, and to try to replicate empirical observations using computational models. Lastly, an alternative approach would be to use lab experiments to test and gain further insight into the mechanisms at work.

To summarize, it is without doubt that numerous exciting opportunities exist for future work at the intersection of complexity and competitive advantage. However, it will be vital for research in this domain to broaden its current focus and start considering a wider range of aspects and interdependencies that characterize the strategy field – in order to prevent a premature lock-in and pave the way towards higher peaks on the research landscape.

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29

Complexity Theory and Corporate Strategy

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INTRODUCTION

Corporate strategy focuses on the central strategic choices that are faced by multi-business firms with regard to creating competitive advantage and enhancing corporate performance. Multi-business firms are typically structured using multi-business-unit (BU) organization (sometimes termed M-form) in which the firm is divided into business-units (BUs) that are focused on particular product-market segments and yet also have some degree of interconnection with one another (e.g. shared human resource function, bundled products, or collaborative R&D projects), and are led by a corporate office (Chandler, 1991). The central strategic choices that form the substance of corporate strategy are typically considered to be: (1) motivation and control of the firm's BUs, (2) collaborations across BUs, and (3) firm scope. In this chapter, we present and contrast traditional perspectives on corporate strategy with a more recent view – a complexity perspective on corporate strategy – informed by theories of complex adaptive systems and with a growing body of empirical support.

Given the theoretical and practical importance of multi-business firms (Freeland, 1996; Galunic and Eisenhardt, 2001; Micklethwait and Wooldridge, 2003), the multi-BU organizational form has been examined from multiple theoretical perspectives, including information processing (Chandler, 1962; Galbraith, 1973), transaction cost economics (Williamson, 1975), and social network theories (Hansen, 1999; Hansen, 2002). These theories provide varied explanations for how the multi-BU organizational form generates value (Martin and Eisenhardt, 2010) such as by effective strategic decision making (Chandler, 1962; Galbraith, 1973), mitigation of opportunism (Berle and Means, 1932; Murmann and Frenken, 2006), and enhanced value creation through cross-business-unit collaboration (Helfat and Eisenhardt, 2004). While information processing, transaction cost economics, and social network theories offer important insights about corporate strategy, our purpose is to sketch corporate strategy from the alternative perspective of complexity theory.

The traditional theories of multi-BU organization, notably information processing and transaction cost theories, take a corporate-centric perspective on corporate strategy. That is, corporate executives play the most critical role in corporate strategy by shaping the overall course of action and the broad architecture of BUs within firms. These theories also assume that corporate executives have the required information to make the central choices of corporate strategy and that they have the appropriate incentives such that they adopt the perspective of the entire firm (Chandler, 1962; Hill et al., 1992; Gupta and Govindarajan, 2000). In contrast, BU executives are assumed to have the most relevant knowledge for running their businesses, but also lack the vision and requisite information to identify collaborative synergies across the corporation and to set the scope of the firm. Moreover, particularly in the transaction cost economics formulation, BU executives are assumed to be likely to pursue self-interest that benefits them personally or benefits their BUs, but not necessarily the entire firm. To counteract this potential opportunism, corporate executives rely on incentives to align the interest of the BUs with the interests of the firm and on monitoring BU behaviors (Williamson, 1975; Hill et al., 1992). In addition, corporate executives are typically seen as responsible for orchestrating synergistic collaborations across the firm such as cross-BU collaborations on R&D projects, shared sales forces, and so forth. Corporate executives also set the horizontal and vertical scope of the firm. At the heart of these corporate-centric theories is an emphasis on efficiency as the driver of competitive advantage and superior performance in relatively stable markets.

In contrast, practitioners and scholars who view corporate strategy from the complexity perspective assume that the multi-BU organization is a complex adaptive system (CAS) consisting of modular, loosely linked, and unique BUs (Anderson, 1999). While this view of overall organizational structure is consistent with the well-known M-form, it differs from traditional information processing and transaction cost theories in its understanding of, and hence prescriptions for, the distribution of power and decision making, the roles of the various executive-actors and the management of important organizational processes for change. For example, when this approach is enacted the strategies of BUs emerge from the individual BUs such that BUs executives act relatively autonomously and loosely guided by simple rules that enable improvised action to adapt to real-time conditions (Eisenhardt and Sull, 2001); and a more decentralized distribution of power shapes cross-BU collaborations (Martin and Eisenhardt, 2010). Instead of corporate-driven, these collaborations emerge from the self-interested interactions of individual BUs. Moreover, while the extant theories of corporate strategy emphasize the design of structures and incentives, complexity theory emphasizes the processes (sometimes termed 'dynamic capabilities') that recombine the firm's resources and coevolve the firm with the environment (Eisenhardt and Martin, 2000). These processes include the *morphing* of the BUs in the context of simple rules to fit the environment (Eisenhardt and Sull, 2001; Rindova and Kotha, 2001), the *rewiring* of the collaborative connections among BUs (Martin and Eisenhardt, 2010), and the *patching* of the architecture of BUs within the firm by frequently adding, splitting, exiting and combining extant BUs (Galunic and Eisenhardt, 2001; Gilbert, 2006). Complexity theory thus calls for a fluid organization with multiple motors of adaptation that enable the firm to coevolve with changing environments. The key challenge for corporate strategy from a complexity point of view lies in finding the right balance of too much and too little structure. Too much structure is overly rigid while too little is too chaotic.

The purpose of this chapter is to outline corporate strategy from the perspective of complexity theory. Specifically, we apply the complexity perspective to the central strategic choices of corporate strategy, and compare the implications of complexity theory with those of traditional theories. We begin by sketching some key insights from complexity science. We then examine multi-business organization as a CAS. We continue by describing how the central choices of corporate strategy unfold vis-à-vis the morphing of BU strategies using simple rules, rewiring of collaborations across-BUs to capture corporate synergies, and patching of the BU architecture that sets the scope of the firm. Overall, we highlight the emergent and process-driven character of corporate strategy, the unique roles played by different executives, and the critical points of comparison between complexity theory and extant perspectives.

ESSENTIALS OF COMPLEXITY THEORY

A major paradigm shift from a reductionist to a holistic perspective has taken place across scholarly disciplines. Since the 1600s, reductionism has been the dominant scientific method in Western theories with prominent adherents such as Descartes and Newton. For example, Descartes (2006: 17) aspired 'to divide all the difficulties under examination into as many parts as possible, and as many as were required to solve them in the best way'. As a result, large problems were broken down into simpler, constituent problems; and it was assumed that knowledge of a system's constituent parts would prove adequate for understanding the system as a whole. But while this decomposition had advantages, such pigeonholing often obscured understanding of the entire system with its emergent, 'complex' behavior (e.g. self-organization, nonlinear dynamics, and power-law distributions of system-level phenomena). Rather, understanding complex systems requires examination of their structural dynamics – i.e. constellations of elements which comprise the system, the connections and interactions among elements, their similarity, and their degrees of freedom.

Rooted in general systems theory and theories of nonlinear dynamical systems, complexity theory has been used across a variety of scholarly disciplines including biology (Kauffman, 1993, 1995, 2004), chemistry (Prigogine and Stengers, 1984; Bonchev and Rouvray, 2005), computer science (Holland, 1975, 1996, 1998; Simon, 1996), physics (Gell-Mann, 1994a; Bar-Yam, 1997; Gell-Mann and Tsallis, 2004; Ellis, 2005), entomology (Gordon, 1999), and economics (Arthur, 1989; Anderson et al., 1998). As concerns management, complexity theory has also been developed within organization theory (Simon, 1962; Anderson, 1999; McKelvey, 1999; Chiles et al., 2004) and applied to corporate strategy (Levinthal, 1997; Brown and Eisenhardt, 1998; Macintosh and Maclean, 1999; Rivkin, 2000). Across all of these fields, simulation studies have proved to be a powerful method for generating insights into whole-part relations and the phenomenon of complexity.

The term 'complexity' refers to a specific type of behavior that emerges from complex adaptive systems (CAS) (Holland and Miller, 1991; Gell-Mann, 1994a; Miller and Page, 2007), not to the system itself.[2] A CAS is comprised of partially connected agents whose interaction gives rise to the 'complex' behavior that is characteristic of these systems (Gell-Mann, 1994b). Within a CAS, each agent acts autonomously according to specific rules and in response to information received via connections to other nodes and in coevolution with the environment. The behavior of more-structured systems can be succinctly characterized by regularities produced by structures, which lead to ordered and predictable outcomes. The behavior of less-structured systems can also be briefly described by the well-defined property of randomness in mathematics. In contrast, in systems with moderate structure, the emergent behavior is an unpredictable combination of behaviors that are neither completely structured nor random, and so cannot be briefly described. Rather, they are 'complex' behaviors.

This transition phase between randomness and regularity is denoted as the 'edge of chaos' (Langton, 1990)[3] in which paradoxical and indeed "complex" behavior emerges. In the natural world, the edge of chaos is a transition point or zone, characterized by rich life forms and the emergence of complicated phenomena like the tidal area between sea and land, the transition zone at 32°F between water and ice, and the area around underwater heat vents. There exists a 'dissipative' equilibrium – i.e. it is an unstable such that the system is continually falling away from equilibrium. To maintain such an equilibrium, energy must constantly be injected into the system (Prigogine, 1984). A central focus of complexity theory is on the structures (e.g. rules, scale, formalization, and connections) which allow reaching and operating at the edge of chaos (Kauffman, 1995).

Two principal propositions are central to complexity theory. The first addresses the optimal amount of structure, and is rooted in the trade-off between efficiency and flexibility (Davis et al., 2009). It argues that partially connected systems of agents are higher performing than ones that are highly coupled or highly decoupled (Kauffman, 1995; Langton, 1990; Gell-Mann, 1994a). When the constitutive elements of the system are over-connected, the system becomes gridlocked and cannot adapt to new opportunities. At the extreme, it reaches a 'complexity catastrophe' in which the organization is able to address too few opportunities to succeed. In contrast, if the elements are under-connected, the system becomes too disorganized and error-prone to adapt. At the extreme, it reaches an 'error catastrophe' in which it lacks enough traction to capture enough opportunities. Thus, only partially connected systems (i.e. a moderate degree of structure) are both flexible and efficient.

The second proposition deals with the relationship between optimal structure and the environment. It argues that, as environmental unpredictability decreases, greater efficiency and so more structure become advantageous. In such environments, executives can develop structures that mirror patterns in the environment. In contrast, as environmental unpredictability increases, greater flexibility and so less structure are preferred (Davis et al., 2009). Moreover, since such limited structure is highly mistake-prone and attention-demanding, the range of optimal structures narrows to edge of chaos that is difficult to find and maintain. The optimal degree of structure (and the robustness of its range), therefore, depends upon the unpredictability of the environment (Eisenhardt and Sull, 2001).

ORGANIZATION AS A COMPLEX ADAPTIVE SYSTEM

A key premise of this chapter is that firms with the multi-BU organizational form are high-performing when they are managed and allowed to function as complex adaptive systems. Specifically, their BUs are unique 'agents' that are partially connected such as through common culture, consistent human resource practices, and discrete collaborations among BUs. When these connections are moderate, then the firm is likely to be high performing. Further, when environmental unpredictability increases, the optimal amount of structure (i.e. scale of business units, degree of formalization and centralization, and number of connections among agents) decreases.

Although the relevant empirical research within the organization theory and strategy literatures often does not explicitly use complexity theory *per se,* this research is nonetheless broadly consistent with the propositions of complexity theory. An example is Chandler's (1962) classic study of strategy and structure in diversified firms. This work describes how DuPont's centralized functional organization hindered its ability to adapt to rapidly evolving markets. DuPont went from being a single business firm prior to the First World War to operating in diverse businesses in many markets in the post-War period. The company retained its centralized functional form and performed poorly. In reaction, its executives adopted multi-BU organization by structuring the firm into numerous, loosely linked and modular BUs. As Chandler (1962) relates, the firm became high-performing. In a contrasting case, Chandler (1962) indicates how Alfred Sloan brought together previously independent producers to form a set of loosely coupled, modular businesses that became General Motors. A key point is that, although these firms began from different starting points (i.e. over-structure at DuPont and under-structure at GM), both GM and DuPont became high-performing when they organized as complex adaptive systems.

Other research also supports the complexity theory proposition that firms with loosely coupled, modular BUs (i.e. complex adaptive systems) are high-performing. For example, Tripsas (1997) finds that firms in the typesetter industry with geographically dispersed R&D units were more high-performing than other firms. Their modular structures of loosely connected, but separate, 'agent' units spurred rapid innovation. These structures encouraged competition that was highly motivating, increased the variety of scientific approaches, and enabled working on overlapping technologies at different locations. In contrast, firms with more centralized and less modular structures lacked sufficient variety, i.e. requisite with that of their environment. Overall, the study confirms that firms with organizations that more closely resembled complex adaptive systems were more high-performing. Bradach (1997) provides another example. Examining five large US fast-food chains, he observes the benefits of two, unique store types within these successful firms – i.e. the simultaneous use of company-owned and franchised units. While company-owned units promoted efficiency with rapid deployment of innovations and uniform practices that ensured product and service consistency, the franchised units promoted flexibility by greater experimentation and innovation. By combining these two types of units, the firms balanced efficiency and flexibility to achieve high-performance.

Similarly, extant organizational theory and strategy literatures support the second complexity proposition that, when the environment is unpredictable, high-performing organizations are less structured. For example, this argument is well-supported in contingency theory studies that find organic structures to be high-performing when environments are volatile and mechanistic structures to be high performing in stable environments (Burns and Stalker, 1961; Davis et al., 2009). Another example is Gilbert (2005), who examines the organizing reactions of multiple newspapers to the environmental discontinuity that marked the emergence of the Internet. When addressing this disruptive nascent market, most newspapers retained the tight, structurally integrated organization that they had successfully used in their prior, stable environment. This monolithic organizing structure favored efficiency, and so proved to be inadequate in the unpredictable, Internet environment. Only those newspapers with executives who separated their established newspaper and Internet businesses into distinct and loosely coupled BUs were successful. Overall, the extant literatures provide support for the primary arguments of complexity theory – i.e. multi-business firms that are organized as complex adaptive systems are high-performing, and that their optimal amount of structure decreases with increasing environmental unpredictability. We turn now to consider the complexity perspective on the central choices of corporate strategy and its differences with traditional theoretical views.

MORPHING WITH A SIMPLE RULES STRATEGY

As described earlier, three strategic choices form the substance of corporate strategy. The first centers on how to *motivate and control*

BUs and their managers. The traditional view is based upon information processing theory (Chandler, 1962; Galbraith, 1973; Galbraith, 1974) and transaction cost economics (Williamson, 1975). Information processing proposes the division of responsibilities within the firm – i.e. corporate executives engage in high-level strategy, while the BU managers focus on the day-to-day operations of their business units and their BU strategy. Transaction cost economics adds the assumption that BU managers are likely to be opportunistic in their pursuit of self-interest. Therefore, corporate executives have the additional role of monitoring the performance of BU managers such that they instead seek the interests of the corporation. Alternatively, corporate executives control and motivate BU managers through 'high-powered' incentives which reward BU managers for the performance of their BUs and stand in contrast to 'low-powered' incentives which are based on the performance of the corporation. Overall, these theories emphasize that multi-BU organization is efficient through monitoring, incentives, and the rational partitioning of decision-making to the best-informed and motivated executives.

In contrast, complexity theory emphasizes the emergence of BU-level strategy from the improvisational actions of BU managers within the guidelines of simple rules. Improvisation enables firms to adapt to rapidly evolving markets with frequent strategic renewals (Agarwal and Helfat, 2009) that we term morphing. A prototypical exemplar is Hewlett Packard (HP). The firm started as an instruments company, but its BUs morphed the firm into a computer firm and then into printing by using a highly decentralized organization of loosely coupled, modular BUs and an improvisational process of adaptation driven at the BU-level as anticipated by complexity theory.

Central to the complexity theory perspective on managing BUs is the *'strategy of simple rules'* (Eisenhardt and Sull, 2001; Davis et al., 2009). Managing BUs consists of focusing on a few key processes and related simple rules that enable the improvisational capture of new opportunities at the BU-level (Bingham et al., 2007). In other words, complexity theory proposes simple rules to guide autonomously acting BUs such that each BU agent acts accordingly to some schemata (Rumelhart, 1984) or rules (Gell-Mann, 1995). These rules guide behavior in the absence of central coordination such that non-chaotic but 'complex' behavior emerges (Reynolds, 1987; Holland, 1996; Axelrod and Cohen, 1999). The result is that BUs morph in coevolution with the market.

A useful example of this morphing of BUs is described in the comparative case studies of Internet rivals, Excite and Yahoo!, between 1993 to 1998 (Rindova and Kotha, 2001). This early stage of the Internet was highly unpredictable, and so required firms to have some, but modest, structure. In particular, Yahoo executives focused on several processes including alliance formation and product development, and developed a few rules to loosely structure those processes to enable improvisation. For example, Yahoo's simple alliance rules included (1) no exclusive deals and (2) basic service is always free. Yet within these rules, BU managers at Yahoo had a significant flexibility to pursue a variety of unanticipated and often successful alliances. Overall, both firms (but especially Yahoo) used simple rules to morph from being search engines to being Internet destinations, and subsequently Internet portals.

Similarly, Brown and Eisenhardt (1997) focus on how the successful BUs of firms in the computing industry used a few rules within the product development process (e.g. responsibility assignments, priorities) to morph via frequent release of new products. As a result, these firms frequently renewed their product portfolios through improvisation. As one developer commented 'We fiddle right up until the very end' (p. 11). The resulting interplay of structure and improvised action gives rise to 'complex' behavior that is neither well-structured nor completely random (Gell-Mann, 1995). So much like a jazz band (Berliner, 1994;

Hatch and Weick, 1998), BUs morph (Miner et al., 2001).

A key difference between traditional theories of managing BUs and complexity theory is *executive roles*. From the complexity perspective, strategy is not centrally determined by corporate executives, but rather emerges from BUs. In other words, BU managers, who adapt their business activities to changing market within the context of moderate structure, create strategy. A telling example is Burgelman's (1994) study of Intel in which he examines the emergence of autonomous actions at low levels of the firm in Intel's exit from the DRAM business. The crucial behaviors were the reallocation of resources by mid-level managers who were following simple rules surrounding priorities for manufacturing capacity. This action changed the trade-off between the mature DRAM business and the nascent microprocessor business. The later decision to exit DRAMs by corporate executives was in fact *ex post* (Burgelman, 1994, 2002). Thus, while traditional theories emphasize incentives and monitoring to motivate and control potentially opportunistic BU managers, complexity theory emphasizes having the appropriate processes and the right rules (both content and number) in place such that BU managers can flexibly and efficiently morph their businesses in coevolution with their relevant environments.

Finally, recent research develops a richer understanding of the strategy of simple rules by examining more closely the nature of simple rules. In a multiple-case, inductive study, Bingham et al. (2009) examine the internationalization process of entrepreneurial firms to understand how portfolios of rules develop over time. They find that the relevant rules focus on capturing opportunities, and that rules for selecting and executing opportunities are learned first. Later, rules surrounding the priority, sequence, and timing of multiple opportunities are learned. Moreover, the authors find that executives consciously cycle through elaborating and then simplifying their rules to maintain moderate structures over time. That is, they 'under-specify' their portfolio of rules firms by engaging in 'simplification cycling'. Moreover, BU executives actively varied the level of abstractness of the deployed rules. Lower abstraction renders a rule concrete and sharply specified. For example, one BU replaced its opportunity selection rule from 'retail customers' to 'grocery customers' (lower abstraction). Conversely, higher abstraction renders a broader, more general rule that is more disassociated from particular instances. For example, one BU raised the abstraction of its selection rule from 'governments and banks' to 'large organizations with proprietary information and the ability to pay'. Recent research has analysed the processes how firms develop simple rules based on their process experience (Bingham and Eisenhardt, forthcoming). Overall, this work identifies the types of rules, their patterns of being learned, and their focus on effective opportunity capture such that BUs are able to morph. Table 29.1 summarizes key differences between traditional and complexity perspectives as concerns the motivation and control of BUs.

REWIRING CONNECTIONS AMONG BUSINESS-UNITS

A second strategic choice at the heart of corporate strategy is the identification and implementation of synergistic collaborations among BUs. The existence of synergies is a prime rationale for the existence of the multibusiness corporation (Panzar and Willig, 1981; Bailey and Friedlander, 1982; Teece, 1982; Milgrom and Roberts, 1990). The potential for synergies across businesses is often central to the strategic logic for firm-level moves such as diversification and acquisition (Goold et al., 1994; Graebner, 2004). Indeed, Bowman and Helfat (2001) have argued that cross-business collaborations are a significant source of value creation for the diversified corporation. Research has shown

Table 29.1 Motivation and control of business units (BUs)

	Traditional perspectives	*Complexity perspective*
Objective	Efficient alignment of BU actions with firm objectives	Effective morphing of BU in coevolution with market
Role of corporate executives	Monitor BU actions and reward BU managers with 'high-powered' incentives	Appoint high-quality BU managers and reward them with 'high-powered' incentives
Role of BU managers	Identify and execute business strategy	Identify and execute business strategy in accordance with corporate-wide simple rules, to morph their BU
Focus	Strategic content	Strategic content and moderate number of rules
Steps	Identify attractive markets Locate defensible position Fortify that position	Identify key processes with attractive opportunity flow Determine simple rules for capturing opportunities
Risk	BU managers will be too slow and rigid to change	BU managers will be too tentative in executing on promising opportunities

that the connections among BUs are a likely explanation for sustained inter-firm differences in profitability (Brown and Eisenhardt, 1997; Levinthal, 1997; Rivkin, 2000; Bowman and Helfat, 2001; Lenox et al., 2006). Yet despite its importance, the effective capture of synergistic value across BUs through collaborations has often proved challenging even for otherwise high-performing firms such as Johnson and Johnson (Hill and Hoskisson, 1987).

The traditional theoretical perspectives on cross-BU collaborations take a corporate-centric view. They emphasize that centralized identification of synergistic collaborative opportunities by corporate executives and implementation led by corporate executives, with firm-wide incentives for BU managers, are most likely to yield high-performing, cross-BU collaborations (Hill et al., 1992). These arguments rest on several assumptions. First, according to information processing theory, corporate executives have superior information about collaborative opportunities, and the appropriate authority to identify and implement the most promising cross-BU connections (Chandler, 1962, 1991; Sloan, 1963; Freeland, 1996; Gupta and Govindarajan, 2000). It is also assumed that potentially high-performing collaborative opportunities are well-formed and obvious to these corporate executives. Further, as argued by transaction cost economics, corporate executives have the appropriate firm-wide incentives for finding and leading cross-BU collaborations while BU managers who might otherwise pursue self-interest can be motivated to collaborate by firm-wide incentives (Williamson, 1975; Hill et al., 1992). Furthermore, corporate executives are assumed to be able to resolve conflicts among collaborating BUs (Boulding, 1964) and enforce the sharing of resources (Berg, 1973; Pitts, 1977). Indeed, from the perspectives of information processing theory and transaction cost economics, a primary responsibility of corporate executives is the development of cross-BU collaborations (Chandler, 1991; Collis and Montgomery, 2004).

In contrast, complexity theory takes a BU-centric view in which high-performing, synergistic collaborations across BUs emerge from the interactions among BU members engaging in their own self-interested actions (Martin and Eisenhardt, 2010). These collaborations often begin with serendipitous problems and opportunities rather than being explicitly pursued and planned. As a consequence, collaborations often start informally and at low organizational levels such as when low-level BU engineers realize that working together on shared product components might be mutually beneficial. BU general managers and their organizations then develop these promising emergent collaborations by rewiring the firm's web of cross-BU connections through the formation of collaborations. Frequent 'rewiring' (Martin and Eisenhardt, 2010) allows the firms to coevolve with changing markets, target new growth opportunities, and generate innovation (Wuchty et al., 2007). A well-known example is Disney, a firm that frequently forms and disbands collaborations among diverse BUs including theme parks, TV channels, retail stores and movies (Eisenhardt and Galunic, 2000). The result is extensive synergistic value creation among Disney's various businesses including well-known collaborations around proprietary characters such as the Lion King as well as lesser-known collaborations that leverage competences throughout Disney such as managing restaurants.

An in-depth example of rewiring is the study of cross-BU collaborations within six software firms (Martin and Eisenhardt, 2010). Examining both a high- and low-performing collaboration in each firm, the authors find that serendipitously discovered collaborative opportunities by BU members are more likely to create high-performing cross-BU collaborations than planned collaborations identified by corporate executives. In this BU-centric view, collaborations among BUs are not preplanned, but emerge in reaction to opportunities such as collectively developing shared product components and problems such as scarce resources and competitive threat. For example, Martin and Eisenhardt quote one BU manager: 'It was really a groundswell. … They [engineers from the 2 BUs] just started meeting to solve the problem. It did not come from an executive [corporate] level where it's, "Thou shalt do it"'. Moreover, in contrast with traditional views, these collaborative opportunities are typically ill-defined such that it is not obvious *a priori* how or whether to pursue them. So BU members further develop promising collaborative opportunities through deliberate learning activities such as experimentation that involve customer focus groups or technological prototyping and deconstruction of past successes and failures in similar collaborations. This learning serves to clarify the value of the collaboration and how best to proceed as well as builds support for the collaboration among participating BUs. Martin and Eisenhardt (2010) also find that the ultimate decision to implement and the implementation approach rest with BU general managers. Thus, high-performing cross-BU collaborations are driven at the BU-level as anticipated by complexity theory, and enable BUs to recombine existent knowledge to generate innovations and growth (Hargadon and Sutton, 1997; Wuchty et al., 2007). In contrast, the authors find that a corporate centric approach is not effective. Rather, corporate executives lack detailed knowledge of the BUs, are overly confident of their own ability to spot high-performing collaborative opportunities (Roll, 1986; Hiller and Hambrick, 2005) and are too dismissive of the challenges that are posed by the implementation of collaborations (Freeland, 1996). Yet, given their authority within the firm, corporate executives can nonetheless impose collaborations on their firms.

A key difference between traditional theories of identifying and implementing synergistic cross-BU collaborations and the complexity view is *executive roles*. From the complexity theory view, collaborations emerge from BUs and are shaped by BU managers. Thus, collaborations are decentralized. But while corporate executives are not leading collaborations, they nonetheless set the stage for high-performance by facilitating their emergence and implantation. They do so by reducing the costs of identifying and transferring knowledge among BUs (Hansen, 1999), creating mutual trust and fostering informal relationships among BU managers (Tsai, 2000), and appointing high-quality BU managers in whom others will be confident. Thus, they may institute simple approaches such as placing coffee bars in key office areas such that BU members have opportunities to meet serendipitously (Brown and Eisenhardt, 1997), or more complicated approaches such as fostering cross-BU career paths (O'Reilly III and Tushman, 2004: 79; Williams and Mitchell, 2004; Williams and Karim, 2008), allowing double-counting of collaboration-related revenues to participating BUs, and employing 'synergy managers' whose job consists of connecting BU members who might have common interests. Overall, the key point is that, while corporate executives do not effectively identify and implement collaborations across BUs, they can set the contexts that enhance the likelihood that useful collaborations will emerge and be successfully implemented.

A second key difference between traditional theories and complexity theory is the role of *incentives*. Transaction cost economics, in particular, emphasizes the importance of firm-wide incentives for BU managers to encourage their cooperation in cross-BU collaborations. The notion is that BU managers will not be motivated to cooperate unless their incentives are aligned with the fate of the entire firm. In contrast, complexity theory assumes that high-performing collaborations are motivated by the self-interested actions of the BU managers and so incentives based on BU performance encourage the formation of synergistic collaborations. Here the argument is that it is difficult and even impossible to identify the optimal, high-performing collaborations and so the best approach to identifying such optimal collaborations is to identify those collaborations that each involved BU sees as adding local, BU-level value. Thus, the complexity perspective contrasts with a collectivist culture where collaboration for the sake of collaboration is valued as well as with a top-down, centralized view (Eisenhardt and Galunic 2000). Further use of high-powered incentives based on BU performance is simple, and more effective than more complicated blends of high- and low-powered incentives (Wageman and Baker, 1997; Kretschmer and Puranam, 2008).

Finally, a particular interesting notion from the lens of complexity theory is that a *moderate number of cross-BU connections* is highest-performing with this optimal number declining with increasing environmental unpredictability (Davis et al., 2009). So while traditional views implicitly assume that more collaborative connections among BUs are more value-creating for the firm, complexity theory does not. Rather, fewer collaborations can be higher-performing when they focus the attention of BU managers on successfully executing the most promising collaborations while also ensuring that they attend to managing their BUs effectively. Thus, a moderate number of cross-BU connections renders the highest performance by balancing flexibility and efficiency. Indeed, over-connected BUs become gridlocked, and unable to morph. A good example is Vail Ski Resorts, a firm consisting of multiple ski destination resorts in the US. The firm was assembled through a series of acquisitions with the intent of driving synergistic value creation top-down across the resorts (Eisenhardt and Galunic, 2000). But the resulting over-connection reduced the individual uniqueness of the resorts and stifled their flexibility to adapt to their local environments. To repair the damage, executives eliminated numerous ties and set the conditions that enabled the emergence of new, more high-performing connections from the ski resorts themselves. Unexpectedly a lower number of collaborations created greater synergistic value among the BU-resorts than greater connection. The central point is the importance of focusing on only a moderate number of potentially high-performing collaborations rather than pursuing all possible collaborations as anticipated by complexity theory. Table 29.2 summarizes key differences between traditional and complexity perspectives as concerns the identification and execution of synergistic BU collaborations.

Table 29.2 Identification and execution of synergistic BU collaborations

	Traditional perspectives	*Complexity perspective*
Objective	Efficient cost synergies	Effective rewiring of BU connections in coevolution with markets
Role of corporate executives	Identify promising, well-defined collaborations, with fiat to execute given to BUs	Set the context in which cross-BU collaborations can emerge from BU-driven initiatives
Role of BU managers	Corporate driven: Execute cross-BU collaborations identified by corporate executives	BU driven: Lead deliberate learning to shape and vet promising, but ill-defined cross-BU collaborations, make decisions to collaborate with other BUs, and collectively execute
Focus	Content of synergistic collaborations	Content and number of synergistic collaborations
Steps	Corporate executives seek collaborative opportunities Corporate executives make decision to collaborate BU managers plan and execute	BU members serendipitously find collaborative opportunities BU members deliberately learn about the collaboration Multi-business team of BU managers decide to collaborate and execute
Risks	Poor collaborations are executed Good collaborations are poorly executed Too many collaborations executed	Optimal, firm-wide collaborations are neglected

PATCHING THE ARCHITECTURES OF BUSINESS-UNITS

A third strategic choice of corporate strategy centers on the determination of horizontal and vertical scope within the firm. From the perspective of traditional theories, the dominant logic for the scope of the firm is efficiency (Porter, 1980). Vertical scope, i.e. the decision to make or buy, is shaped by minimizing the transaction costs associated with small numbers bargaining and asset specificity (Williamson, 1975) and gaining the economies of scale associated with greater volume. Horizontal scope, i.e. the decision in which markets the firm is active, is shaped by the efficient sharing of resources across BUs (Teece, 1980). Thus, executives should expand the horizontal scope of the firm if there are opportunities to leverage existing resources. Overall, this perspective emphasizes efficiency and thus appropriate scope, but does not consider how firm executives structure their internal organization to achieve scope efficiencies or adjust that scope as environmental conditions shift.

In contrast, the complexity theory view focuses on the patching process by which executives frequently realign firm scope in coevolution with the environment (Eisenhardt and Brown, 1999). By patching we mean the process by which executives set the architecture of the firm and its scope by adding, eliminating, combining and splitting BUs, and transferring product-market charters among them. The notion is that the corporation is a complex adaptive system in which the patchwork or architecture of BUs is continually realigned with the environment via patching. Thus, the complexity theory view not only focuses on scope, but also on the internal architecture of the system of BUs. Moreover, as environments change, the BU architecture may become obsolete. Firms can correct these misfits by combining, splitting or adding BUs or reassigning an extant BU to a new product-market domain[4] (Galunic and Eisenhardt, 1996, 2001; Eisenhardt and

Brown, 1999). Thus, by patching, firms are able to target changing opportunities, create and recombine resources, and generate innovation (Macintosh and Maclean, 1999; Lichtenstein, 2000; Karim, 2009). A well-known example of patching is Dell Computers in which the firm reassesses its architecture of BUs on a quarterly basis for many years. Another exemplar is Hewlett Packard's (HP) where executives relied on patching to grow their instruments, computing, and printing businesses. To ensure focus, executives frequently rearranged BUs, lopping off pieces and transferring them to new and existing BUs (Eisenhardt and Brown, 1999). Overall, by engaging in patching (Ciborra, 1996; Levinthal and Warglien, 1999; Galunic and Eisenhardt, 2001), firm executives can create corporate value in a way that is uniquely available inside corporations and not easily replicated by the market.

Galunic and Eisenhardt (1996, 2001) examine the patching process within a particularly successful, technology-based firm by studying the frequent re-assignment of a product-market domains (or charters) to BUs. They find that executives within the firm (termed Omni by the authors) frequently revisit the match of BUs, their skills, and business opportunities with the environment, and realign them as appropriate. This generates competition for charters among BU that not only is beneficial for the BU-domain fit, but also increases the overall competitiveness, fit, and flexibility of the firm. Corporate executives act as referees of the BU competition, find safe BU 'homes' for orphaned charters and reinvigorate flagging BUs by assigning new charter opportunities to them.

There are several antecedent conditions that enable effective patching (Eisenhardt and Brown, 1999). First, the firm has to be organized such that BU modularity exists whereby the firm is broken into discrete, unique BU chunks (Schilling and Steensma, 2001; Langlois, 2002). Second, fine-grained comparable business metrics are needed to allow corporate executives to recognize general patterns in the environment, identify non-performing BUs, and facilitate the novel combination of extant BUs. Third, companywide compensation parity is important because it mitigates barriers to moving employees among BUs. These conditions facilitate the realignment of BUs and product-market charters that is at the heart of patching.

A key difference between traditional theories and the complexity theory view is *executive roles*. Prior theory emphasizes the corporate executives set firm scope based on efficiency criteria. But there is no substantive consideration of the process by which this occurs. In contrast, complexity theory emphasizes a more complicated political process involving corporate executives and BU managers who may be competing with one another for product-market opportunities. This process includes spotting opportunities, breaking up BUs that are too big for effective morphing, combining ones that are too small for scale efficiency, and refereeing by corporate executives among BUs that are competing for converging product-market opportunities. Consequently, a key skill of corporate executives is pattern recognition of the environment (Ciborra, 1996; Eisenhardt and Brown, 1999) that enables them to recognize trends in how markets evolve to develop corresponding products, services or technologies.

A second key difference is the critical importance of *BU scale*. While it is straightforward to recognize that firm scope and architecture should match distinctive BU competences with corresponding product-market opportunities, the complexity view uniquely emphasizes the importance of BU scale that fits with unpredictability of the relevant environments. This means smaller scale that favors flexibility in unpredictable environments and larger scale to favor efficiency in more predictable ones (Eisenhardt and Brown, 1999; Ethiraj and Levinthal, 2004). Small BUs allow the firm to adapt to market niches while large BUs have the advantages of economies of scale, lower coordination costs, and sufficient resources

Table 29.3 Determination of firm scope

	Traditional perspectives	*Complexity perspective*
Objective	Efficient firm scope	Effective patching of firm scope and BU architecture
Role of corporate executives	Determine and execute efficient external boundaries	Match patterns in evolving markets to internal and external boundaries
Role of BU managers	Operate BU within assigned product-market domain	Morph BUs in coevolution with product-market domain(s)
Focus	Content of firm scope	Content of firm scope as well as architecture and scale of BUs
Steps	Identify economies of scale and scope, and transaction costs Set external boundaries of the firm	Referee competition among BUs Fill market 'white spaces' Set internal and external boundaries of the firm
Risks	Misalignment of firm with markets Failure of major corporate reorganizations	Excessive competition among BUs

to pursue opportunities (Eisenhardt and Brown, 1999; Burgelman and Grove, 2007). The optimal scale occurs at the edge of chaos where executives balance efficient scale economies with flexible adaption in unpredictable markets. Table 29.3 summarizes key differences between traditional and complexity perspectives as concerns the determination of firm scope.

CONCLUSION

The purpose in this chapter is to understand corporate strategy from the perspective of complexity theory, and to contrast that understanding with traditional theories of corporate strategy. As noted earlier, complexity theory focuses on the fundamental tradeoff between efficiency and flexibility. So, finding a balance between too much structure and too little, and shifting that balance (and narrowing the range of optimal structures) as environments become more unpredictable are at the heart of the perspective. The complexity theory view is unique in its focus on processes – i.e. morphing in which the BUs coevolve with changing markets by using a simple rules strategy that enables improvisation; rewiring whereby the BUs create new connections (dissolve obsolete ones) among each other to create synergistic value; and patching in which corporate executives combine, split, add or eliminate, and reassign product-market domains to shape firm scope and BU architecture in coevolution with the environment. While these three processes differ, their common roots in complex adaptive systems are evident – i.e. they emphasize the importance of a moderate degree of structure and the pursuit of coevolutionary adaptation with the environment through the decentralized actions of BU-agents who collaborate and compete with one another in pursuit of self-interest.

We propose several directions for future research. Much of the prior work uses case studies and simulations. While these methods provide a useful toolkit for exploring emergent, nonlinear dynamics that are the mainstay of complexity theory, incorporating other methods may generate novel insights. Recently, some scholars have begun to explore questions related to complexity theory and strategy using large-scale quantitative analysis (see for example, Lenox et al., 2010). Another promising direction lies at the intersection of complexity and networks and questions related to corporate strategy and management. Amaral and Uzzi

(2007: p. 1034) argue for example, that there are 'many management scenarios that exhibit network structures and emergent behavior'. These and other scholars extolled the virtues of network analysis as a way to quantify the relationships and interactions that may arise within a firm and that may shape corporate strategy making. A third research direction has less to do with methodology and more to do with theoretical abstraction. Complexity theory, especially as it has been used in simulation models, has developed in an abstract fashion, and focused primarily on the amount of structure in organizations, centralization, and connectedness. There are opportunities to link the theory more explicitly with the real-world characteristics of organizations. As an example, our understanding of optimal organizational design from a complexity perspective might profit from a more concrete conceptualization of actual structural elements. A final research direction centers on temporal dynamics. Extant studies provide little guidance on appropriate pace of change. While the need for corporate adaptation is clear, we have limited knowledge about the optimal speed of doing so. Overall, there exist several opportunities for new research directions that extend complexity theory with new methods and more explicit linkage of the theory to empirical reality.

We conclude by noting Pagels' (1988: 12) argument that 'Science has explored the microcosms and the macrocosms; we have a good sense of the lay of the land. The great unexplored frontier is complexity'. This quotation reflects our view of future research. Indeed, complexity theory adds a rich understanding of corporate strategy to the organization theory and strategy literatures even as it moves those literatures away from the general linear model (Meyer et al., 2005) and toward a more complex and emergent one. Overall, the holistic and systemic focus of complexity theory is an essential lens to better understand 'the causes of things' in major, diversified corporations.

NOTES

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2 Different ways of conceptualizing complexity exist (see for an overview Lloyd, 2001). For example, an alternative stream of research measures complexity capturing characteristics of the system (Simon, 1976). We regard the measuring of the behavior to be more suitable as the structure itself might be very simple but nevertheless give raise to complex behavior as evident in the example of the logistic map equation (Verhulst, 1838; Ausloos and Dirickx, 2006). Thus, even a deterministic and rather simple equation structure can result in some sort of complex behavior and have dynamical trajectories (May, 1976; Cohen and Stewart, 1994).

3 Almost simultaneously, Crutchfield and Young (1990) coined the expression 'onset of chaos' to describe the same type of phenomenon.

4 A product-market domain consists of the goods and services the organization provides and the market or populations it serves.

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30

More than a Metaphor: Complexity and the New Rules of Management

James K. Hazy

INTRODUCTION

This chapter is written for the practicing executive. It explores just how a reader should process the material in this Handbook. In particular, it considers whether the ideas expressed represent only a rich metaphor for the problems faced in practice, or if they represent a more serious contribution to management practice and offer new insights that must be taken into account by thoughtful managers. This is not a trivial distinction, and it has significant implications for the practicing manager.

If the complexity perspective is but a metaphor, it goes like this: If organizations were like organisms, or molecules or lasers, or automatons, this is how they would work. Of course, since we all know that human beings are not molecules, and organizations are not lasers, although these findings are interesting, the reader who is facing practical problems in human organizations every day would take the material written on the pages of this book in a certain way. One would be looking for insights, perhaps, but not actually searching for a new and better way of doing things tomorrow.

If instead, there is more to this complexity model than that. If these ideas can be directly applied to human organizing efforts and if they do indeed tell us what is really going on within our organizations, then that same reader must take a different stance, realizing that he or she had better read this book very closely. If this latter interpretation is accurate, then if you don't understand and make effective use of these ideas, one of your competitors surely will. It may become a matter of survival. The question then is whether this book is an elaborate metaphor or is indeed the beginnings of a new science of management. In this chapter I hope to convince the reader that the latter applies and therefore that this Handbook does indeed deserve close attention.

To advance my argument I begin with an overview and synthesis of key complexity and dynamical systems concepts that have been covered in the volume. Together, these ideas describe a new paradigm in human organizing, management effectiveness and adaptation. In this chapter, I distill what I found in this volume into some of the key lessons for practicing executives that can be derived from this new complexity paradigm. These are organized into what I call the five new rules for management. I conclude with some thoughts about the future. To begin, I summarize a new complexity-informed approach to management.

A NEW PARADIGM FOR MANAGEMENT PRACTICE

In this chapter I assume that organizations can be represented as complex adaptive systems with individuals acting as interdependent, semi-autonomous agents. Further, it is assumed that not only do individual agents learn, but information about the environment can be incorporated into the structure of the system of agents (Hazy, 2008b), and as a result, the collective as a whole can learn through changes to its structure just as its individual agents can learn (Midleton-Kelly and Ramalingam, this volume). In other words, it assumes that organizations can be understood as complex adaptive systems as defined by Holland (1975).

Organizations as stable dynamical systems

Organizations are complex. As many of the chapters in this book argue, they are characterized by nonlinear interrelationships and interdependencies among diverse individuals (Maguire, this volume; Tracy, this volume). It is not surprising that the practice of predicting outcomes within organizations often challenges the limits of simplified analytical models. Linear models that assume that a change to one variable, such as production levels, will have a corresponding 'linear' impact on another variable, perhaps sales, are particularly limited. So many simplifying assumptions must be made in these cases, that the model's predictions seem to ignore 'the real world'. 'Sales' only increases linearly with 'production' under very restricted conditions with respect to demand, consumer preferences, the economic environment, etc. Taking all of these factors into account is often beyond the capacity of the traditional modeling approaches used in business organizations.

Help is on the way. Prietula (this volume) describes one approach to dealings with complexity, computational modeling, an approach that is particularly useful when analytical solutions are not possible. For practical applications, however, this modeling approach is only in its infancy. Fortunately, there has also been progress on the analytical side in the form of nonlinear dynamical systems modeling (Guastello, this volume, 2002; Goldstein et al., 2010; Hazy et al., 2010). This type of modeling describes the combinations of variables that are allowable given boundary and initial conditions, and how combinations of factors change *as a system* over time. In other words, if one seeks to increase sales growth by increasing production, the organization's profitability rate might come down as operating expenses increase for market development and advertising.

As experienced managers realize, however, in addition to these direct impacts, free cash flow might also decrease into the future even more than expected. This is because cash is being consumed in working capital to build inventories and to extend customer credit to fuel growth. Further, time delays in employee hiring might require that staffing activities begin in anticipation of growth, and these may overshoot the mark. If not carefully managed, the delayed effects of increasing payroll and operating costs can increase an organization's burn rate putting downward pressure on cash flow and profits in future periods. If sales growth doesn't materialize as planned, the firm may be more vulnerable to collapse than management thought, particularly if they were locked into linear-thinking (Hazy et al., 2010). Many managers know this, of course, but they don't always act like they do partly because they don't have the right tools to think about these issues. This is where complexity science can help.

Individuals acting within complex organizations

The nonlinear interrelationships among individuals and functions (many of which are not clearly specified in models) and the critical need for effective communication among individuals, functions and departments in respect to these interdependencies, make an organization an exceptionally difficult environment for individuals to navigate. Managers must make sure their actions don't inadvertently create an organization that is unstable or one that can't respond quickly to change. This realization is the basis of the first new rule for management that I describe later: Think evolution of resilience not design for stability.

Organizational stability and individual action within an attractor cage

Several chapters in this book allude to the idea that certain organizational states 'attract' nearby states to them. Merali and Allen (this volume) described structures like warehouses, factories and even websites that, once established, build upon themselves to 'attract' activity toward them. As a general matter, *attractors* within a dynamical system are defined as subsets of all of the possibilities that are likely and such that once the organization assumes one of these configurations it tends to stay there. It attracts other states such that the organization gets stuck in the attractor state. The organization becomes, in a sense, 'stable', bouncing around within the attractor configurations (Abraham and Shaw, 1992; Hirsch et al., 2004; Hazy et al., 2010). It is common for managers to find that their organizations and groups fall into conformity, routines and common modes of operations. When individuals become socialized to common procedures or work rules, whether explicit or implicit, it is reasonable to think of these procedures as 'attractors' in some sense.

The good news from complexity research is that when an organization is subject to an attractor and even if specific events within the system, like sales calls and product development efforts, are not predictable, one can predict that a system as a whole will remain within certain boundaries. These boundaries define what is called an *attractor cage*. Action and choices by individuals that occur in an organization constrained within an attractor cage are said to operate in a *convergent complexity context* where stability is the objective of management actions (Hazy, 2009a).

Experimentation to learn about the environment

Up until this point, I have not described the importance of *initial conditions*. The inherent uncertainty with respect to specific initial conditions, and even the possibility that there are previously undetected drivers of outcomes, can make organizational dynamics unpredictable in the details even as they remain predictable in the aggregate. This type of unpredictability is called *sensitivity to initial conditions* (SIC). In other words, all that can be known specifically is that the system will be in its attractor cage. Where it will be exactly is a matter of probability.

Unpredictability also arises due to chance occurrences, such as employee turnover and customer purchasing decisions, for example. In organizations, surprises happen all the time. The invention of the microprocessor by Intel was serendipitous and unplanned; it was a surprise (Hazy, 2008a; Hazy et al., 2010), and it fundamentally changed the operating environment both within the company and beyond it. Not only was this significant event not predictable or deterministic – i.e. it was an experiment at Intel, a 'butterfly event' as McKelvey (this volume) calls it, in the organization – it also introduced divergence and instability into the organization with dramatic long term effects. In the process, the microprocessor 'experiment' created new information about growth prospects along newly identified independent variables: new technology and a brand new market space (Hazy, 2008a; Hazy et al., in press).

To understand these situations it is useful to consider the role of information and how it is gathered and used (Gell-Mann, 2002) in organizations. In the case of organizations, there is locally relevant information that is largely irrelevant to the organization writ large. Which customer calls are planned on a given day and which employees are in the office, are examples of this. In contrast, there is also more globally relevant information like technology, economic and market trends. Futurists sometimes call information that reflects large scale forces in the environment 'weak signals', 'long waves', or 'mega trends'. As these forces act on the organization, new information – surprise – may become available as events unfold. Under appropriate management (described later), patterns can be recognized and used to predict future states of the organization in its environment. This realization implies the second new rule for management that I describe later: Be open to surprises across all levels of scale.

From the manager's perspective, the demands of maintaining organized stability in human systems can easily be allowed to dominate day-to-day activities and overwhelm attempts to recognize ill-formed patterns that result from large scale forces. However, if distractions can be set aside and the right organizational experiments undertaken, weak-signals may be recognized. Under these conditions, discontinuous change across the organization can occur as agents gather and use the information and the firm absorbs it into its structure (Boisot, this volume). This implies the third new rule for management: Drive effectiveness looking forward (not backward).

Once trends are recognized, the organization may need to change direction. Complexity offers help here as well. The key idea is that the shape of the organization's attractor cage can be changed by modifying the constraints, or boundary conditions, acting on the organization (Guastello, 2002, this volume; Haken, 2006; Goldstein et al., 2010). Certain changes to boundary conditions – for example changes to cultural constraints might allow for the expression of contrary perspectives, or tolerance of projects that are 'off strategy – can cause the organization's attractor state to *bifurcate*. This means that rather than one attractor cage, the organization enters a critical period where it can follow one of several possible paths into the future (Goldstein et al., 2010).

When a system switches from one path to another, for example when Intel changed trajectories from that of a dynamic random access memory (DRAM) chip company to that of a microprocessor firm (Hazy, 2008a), it reflected this kind of bifurcation. At or near the bifurcation point, two attractor cages coexist, and the organization can seem to oscillate back and forth according to random events, or it can appear to be two 'firms' at once. In other words, transitions do not have to be sudden. Intel was both a memory and a microprocessor company for over ten years as it made the transition (Hazy, 2008a). Conditions near a bifurcation point, where two or more attractor cages coexist, enable the organization's leadership to make a choice about future direction. This choice is best made by generating experiments, and from them, identifying and building on what Haken (2006) calls order parameters that describe large scale trends and how the organization can take advantage of them. These conditions embody what has been called a *generative complexity context* (Hazy, 2009b). This is where the future of the firm is generated through experimentation, variation, selection and retention of successful experiments (Surie and Hazy, 2006).

Finding the new way forward

When an organization is operating in a generative context, identifying a preferred state among multiple possible futures is another challenge for leadership. This I describe later as the fourth new rule for management: Build models and encourage focused experimentation. To find these futures, agents in the organization engage in experimentation to generate information about the intersection between the organization and the environment. Individuals in the organization can gather this information and use it as they attempt to recognize patterns and then infer the presence of opportunity potential in the environment. Choosing to follow some of these toward a successful future is one area where individual decisions can influence the organization's direction and success. Along the way, multiple future states – several product possibilities – can become evident. The challenges for individuals who are trying to hold the whole organization together in the face of both local convergence to attractor cages and the generative dynamics that will come to define new attractor cages are a key element of leadership. These conditions constitute what is called a *unifying complexity context* (Hazy, 2009a), and this brings me to the fifth new rule for management: Recognize larger scale patterns and ride waves of renewal (Hazy, 2009b). In the next section, I look at each of these new rules in detail.

FIVE NEW RULES

The insights from this book, when considered in the context of the new paradigm described above, change the rules of management. In addition to what this might imply for executive seminars and business school curricula, I also mean that it changes the 'rules' in the sense of local 'rules of interaction' (Prietula, this volume) that are a central concept to complexity research (Holland, 1975; Tracy, this volume). Changing these rules of interaction changes the structures that emerge through interaction over time. It changes the future, and this is indeed fundamental. Although there are many implications, I divide those that I feel are most important into what I am calling the five new rules of management.

New Rule #1: Think evolution of resilience and not design for stability

One of the most common words one hears in today's organizations is 'design'. This will change as an evolutionary mindset in an uncertain future replaces the false certainty that is implied by the word 'design'. Today, managers design their organizations for control, stability and efficiency. Operations people design their processes; HR professionals design their compensation and benefits programs. Engineers design their products, or the features of their products, or they design an office complex, or a work space, or a manufacturing line. Marketers design their programs and their advertisements, and mailings and so on and so forth. Even finance gurus design derivative instruments.

This design approach, of course, has its advantages. It makes use of what the human intellect and aesthetic sense has to offer in an effort to improve things. However, as a mindset for business management, it has a fatal flaw: It assumes predictability and an end point. A design might be completed, but the system is never finished. A design might be appealing, or aesthetic, or simple, or elegant, but in business, there is no end point in any absolute sense. Each design is actually a 'variation' on previous structures, a trial to be tested in the real world. Each is one step in an endless process of variation, test in context, selection of successful tries, and then the retention of what is helpful and the discarding of failed attempts (Merali and Allen, this volume).

This difference is a critical one for management, because it determines what we manage. In a design mindset, managers reward, well, 'designs'. This misreads the drivers of success. What an evolutionary mindset rewards, in contrast, is the complete process of variation, selection and retention. To do this well, attention must also be paid to the process of identifying appropriate criteria for selection and for retaining the good and discarding that which is not helpful. In my experience, many organizations are not so good at this part, trusting instead their 'designers'. Organizations are not good at stopping things that do not help (Royer, 2003). As a result, organizational artifices are built up, office complexes and management perquisites, for example, that become structural attractors (Merali and Allen, this volume) in their own right. This is bad for business.

Importantly, there is a sense that once something new is tried, once a design trial is launched, the situation is forever changed (Juarrero, this volume), and there is no going back. The launch of the New Coke in 1985 by Coca-Cola is an example of this (Greising, 1998). Human beings have memory, and an individual's history impacts his or her future choices. Although, with the launch of a new trial things are not necessarily better, they have indeed changed. When New Coke failed, the company could not go backward; it could only move forward. The firm's decision to reintroduce Classic Coke, which ultimately replaced New Coke in the market, was an example of effective management from an evolutionary perspective. From the New Coke experience, the CocaCola company, and its CEO, Roberto Goizueta, learned what the market wanted from the company. It wasn't a sweeter recipe. It was a brand. This evolutionary experience was followed by one of the most successful periods in the company's history (Greising, 1998).

In a rapidly changing world, managers must realize that a design, any design is just a 'variation' in the evolutionary sense, but in many cases it is also an irrevocable one to be sure, like a baby being born. Changes once made cannot easily be undone. They can only be changed again. This realization points to the importance of resilience as a characteristic of organizations (Juarrero, this volume). Organizations must be quick to respond to change and also to recover from failed attempts at 'design' as the New Coke fiasco demonstrated (Greising, 1998). That being said, managers must also realize that most design changes are quite superficial, and are usually quite easily shed by a resilient organization. The focus must be on the nature of the variation to be tested, the pressures for and against selection that are being experienced, and the execution of an approach that ensures that fitness enhancing variations will be reinforced while others are quickly abandoned at minimum cost (Hazy, 2008b).

One example of the ascendency of a resilience objective (Juarrero, this volume) as a management practice is offered by Azadegan and Dooley (this volume). They describe the trend toward distributed control systems, an approach which favors quick response and flexibility as an organizational attribute over perceived stability and central control. These authors identify three conditions that must be present for a distributed control approach to succeed. First, there must be an abundance of resources such that each local group has immediate access to the materials they need to respond to events in the environment. Second, there must be enough intelligent agents distributed across the system to respond effectively without regard to direction from a central authority. Third and finally, strong and largely unfettered information connections must be present among these individuals. This later point is necessary so that easily contained local effects can be quickly distinguished from those that reflect more broadly relevant opportunities and threats.

When all three of these come together, distributed control works, and works better than central control. Variations in practice are implemented *and tested* quickly so that success can be reinforced and failure discarded without the political baggage that characterizes central control structures getting in the way. Open communication channels allow successful variations (but not those that are unsuccessful in the environment) to be replicated and widely imitated by intelligent and informed agents who tailor them to fit local circumstances. Organizational resilience is the result because decisions are made quickly by intelligent and informed individuals who are close to events and to the 'sensing' process.

Significant and relevant changes in the system and the environment are recognized quickly and dealt with accordingly without regard to a centrally authorized 'design'. The trend toward distributed control is an example where the new rules of complexity thinking are already informing and improving management practice in the field.

One final cautionary note: just because a particular variation 'sticks' in the company doesn't mean it is fitness enhancing. And conversely, one cannot assume that a change was not helpful just because it didn't stick. The internal dynamics at work within an organization are different (with different drivers) than those that determine what works in the environment and the market. Effective managers must never confuse the two. Changing the organization by implementing 'variations' must be a continuous effort, but this alone is not enough. Managers must reinforce the structures that work and eliminate those that do not while realizing that there is much that is not, and may never be known (Merali and Allen, this volume). So what does an enlightened manager do differently tomorrow? Just as a golfer swings 'through the ball' rather than at it, the enlightened manager must drive execution 'through the design'. The objective is to obtain marketplace feedback and incorporate that feedback into the organization's going-forward plans. To paraphrase the political slogan that is credited with putting Bill Clinton in the White House in 1992: 'It's the feedback stupid!' This brings us to the next new rule.

New Rule #2: Be open to surprises across all levels of scale

Another problem with the idea of design is that it perpetuates the illusion of control and the false belief in absolute knowledge (Juarrero, this volume; Allen and Boulton, this volume; Richardson, this volume). Managers today hate surprises. This is because today's managers operate with an illusion of control that grew out of an organization-as-machine mindset where a surprise is interpreted as indicating a lack of vigilance, diligence or commitment in their subordinates. This leads to a fear in the subordinates with respect to bringing forward 'surprises'. Tomorrow's leaders will welcome certain types of surprises, those that provide hints about future opportunities or threats that were not previously known (Maguire, this volume; Marion and Uhl-Bien, this volume). The right kind of 'surprise' leads to the right kind of learning as Mitleton-Kelly and Ramalingam (this volume) describes. Leaders must be catalysts of learning and are not directors of machine-like operations (Marion and Uhl-Bien, 2001; Uhl-Bien et al., 2007; Goldstein, Hazy and Lichtenstein, 2010; Juarrero, this volume; Marion and Uhl-Bien, this volume)

Managers, even top managers, rarely have all of the answers. They are stuck inside the system as information gatherers and users just like everyone else (Gell-Mann, 2002). They are also often deep inside a cocoon, dependent upon others for all of their information about opportunities and threats in the environment. Being stuck 'inside the system' means that what is happening in the environment becomes increasingly opaque (Boisot and McKelvey, this volume). If one does not see into the environment directly, one must be even more open to and appreciative of surprises. When handled appropriately, they are windows into the future. In fact, as long as the environment is changing, and these days it is doing so more rapidly than ever, one must hope for surprises. They shine light on the unknown *which was always there but was unseen*. In this context surprise has a very specific meaning. A surprise is an event which challenges the efficacy of an organization's collective efforts to construct and use their models that predict the environment (Shotter and Tsoukas, this volume). Gell-Mann calls models used by individuals *schemata* (Maguire, this volume; Gell-Mann, 2002). They can be sophisticated like a dynamical systems model which seeks to address many interacting factors, or they can be embodied in a simple heuristic such as: 'Our customers make buying decisions based upon taste-test preferences'. When a surprise occurs – brand-based preferences at odds with taste-tests were observed at Coke (Greising, 1998), for example – it means that what the organization was positioned to expect, did not actually happen. This is the right kind of 'surprise'. It signals that the organization was (haplessly) going in the wrong direction. This surprise carries with it new information that might enable the organization to better predict outcomes.

There are essentially two strategies to deal with the potential for surprise in the environment. An organization can steel itself, working to harden its shell to maintain its structure and operating assumptions (Boisot and McKelvey, this volume). This is a survival strategy that repulses surprises occurring within its ecology. It, in fact, denies them, holding back potentially disruptive trends and attempting to control the environment (Maguire, this volume; Cilliers, this volume).

Alternatively, an organization can probe the environment through experimentation to learn about the kinds of surprises that it is likely to encounter, gather whatever information is available, and attempt to prepare to address future challenges. Unlike designed variations that were intended to produce a desired (and predictable) result (described under New Rule #1), these experiments are variations that are constructed (designed?) specifically to gather information, and they can be experiments across all scales, from product trials, to new ways to organize operations, for example using a distributed control approach (Azadegan and Dooley, this volume). Andriani (this volume) describes this process for innovation and new product development.

Experiments help to determine if there is a surprise in the environment and to learn what had previously been unknown (Lichtenstein, this volume). Experiments can be spontaneous mutations, or they can be constructed recombinations of other capabilities, but in all cases they are spawned to see what succeeds in the environment (rather than what is acceptable politically) and what does not. They are used to gather information about the intersection of the organization and the environment, even if the underlying reason for success or failure is not yet known. The new information that is uncovered may provide a clue to important forces which were heretofore unknown.

So what does an enlightened manager do differently tomorrow? When presented with a surprise, the first step should be to ask questions about how the surprise came about. What assumptions were made about the company's market and environment, and how does the result provide new or additional information? Of course, the surprise could be due to sloppy work or poor discipline, but this is not the only reason, and incompetence should not be the first possibility explored. A negative, accusatory approach will stop the flow of information. The organization must create an environment that is open to the right kind of surprises and welcome them. They provide one of the most valuable commodities possible: new information. This process is discussed in more detail under Rule # 4, but before going there, I will first discuss a new rule that cautions managers who would choose to steel their organizations against surprises and change.

New Rule #3: Drive effectiveness looking forwards (not backwards)

Complexity researchers often miss the rather mundane reality that most of what managers do is to run the 'machine' of a business organization. As March (1981) put it: 'The conventional, routine activities that produce most organizational change require ordinary people to do ordinary things in a competent way' (p. 573). Importantly, as described in the chapters in this volume, complexity ideas can also inform day to day management by helping managers understand how and why organizations tend to be stable and resilient (Juarrero, this volume) even in the face of their attempts to perturb them. It also can inject healthy skepticism about the efficacy of what's being done, how it is being done, and where the organization is going. In addition, Sterman (2000) has shown that human beings are quite limited in inferring the operations of a system when nonlinear feedback is involved. We take up this point in the next section, but it does imply there is room for complexity ideas to help day-to-day management as well. Important among these considerations is the fact that structural attractors (Allen, 2001; Merali and Allen, this volume) which dominate the 'ordinary' are by definition backward looking. They are built up by repeating what was done in the past.

One insight from complexity is that structural attractors (Allen, 2001), in other words 'all of the current structures' within any organization are always backward looking. Organizing structures like work centers or operating practices are always built up over time from a beginning that was based upon decisions taken, often arbitrarily, at some point in the past. Gell-Mann (2002) calls these 'frozen accidents' (p. 21). They are built up like a river road that was originally an unpaved path that followed the meandering river. Over the years the road is improved, and along the way it is enhanced with ever greater elegance. But at core it remains an artifact built upon what was originally nothing more than a convenience. Most managers are unwitting prisoners of 'frozen accidents' from long before their tenure. Breaking free is not easy. It requires thoughtful planning and precisely timed and executed action.

This realization is personal to me. As a manager, I had always respected processes that came before me, reasoning, in effect, that 'if it ain't broken don't fix it'. I always assumed that 'other smart people put this in place, and so unless I know something different or have better knowledge than they had, I am not going to change it'. But this is not really sound judgement. The 'if it ain't broke, don't fix it' heuristic is far too simplistic. Often, smart people did not put the existing process together, at least not deliberately. Rather, structural attractors often develop part by chance and part by the self-reinforcing flow of the system itself. It's like the river itself meandering across a valley. The meander gets further and further afield over time. Anyone looking from a nearby hill down at a stream meandering across the plains sees that following the stream is not the best way to get from here to there. Likewise nine-times-out-of-ten the way the organization does things is *not* the best way to get it done. Often times, improving the existing process is actually counter productive. Improving a poorly conceived process just makes the ineffective streambed deeper and harder to change the next time. This is how wasted efforts perpetuate, ineffective informal work rules take hold, and internally focused projects rise to prominence. These projects are all about the past and say nothing at all about the future.

Complexity tells you that from an effectiveness perspective, any process, policy, routine, capability or activity looks backward and therefore in a very real sense *is almost always broken*. When a manager doesn't see this, he or she is part of the problem, another bit of silt flowing in the river, dropping to the riverbed in the slow current to decrease rather than increase the 'effectiveness' of the system. Effectiveness must be judged by the best way to do what needs to be done tomorrow, not how to be even better at what we are currently doing, or worse, what we have always done. Maybe the organization doesn't need to do these things at all!

As Lichtenstein (this volume) points out, this is one of the key differences between entrepreneurship and 'business strategy'. With existing firms where the firm has been largely determines and thus severely limits where it can go in the future. For the entrepreneur however, the foundation for the future is only now being laid. These first few structures are critical because they are the seeds that will grow into the organization of tomorrow.

In a certain sense, those decisions that seem the most inconsequential for the entrepreneur – those that are often not even possible to make in an existing business – such as where and how to locate offices and how to organize employee and customer interactions – are indeed the most important. It is these decisions that are the seeds of the firm's emerging structural attractors, and thus it is these decisions that will ultimately determine whether the firm will be flexible and resilient to change going forward. Thus the job of the entrepreneur is much different than the job of the professional manager. Both have their challenges, and neither is any easier than the other. They are very different, but both must first and foremost drive effectiveness by looking ahead, by 'leaning down the fall-line', as my ski instructor likes to say, to feel the pull of the forces that are driving the future. Hidalgo (this volume) describes metrics for social networks and new technologies that will be at the heart of these new approaches.

So what does an enlightened manager do differently tomorrow? Most importantly, every routine and process in the organization is suspect. 'This is how things have always been done', is never a good reason to continue. Each process must be constantly evaluated with respect to how it makes the organization more efficient *going forward.* Maybe it doesn't even need to be done. Perhaps that report that 'somebody else must read' is actually read by no one at all and should be discontinued. The next section describes how managers learn to look ahead.

New Rule #4: Build models and encourage focused experimentation

In a forward-looking, evolutionary view of organizational processes, surprises today offer the promise of better performance in the future. Managers who adopt this perspective are left with the challenge of discovering ways to uncover this information as a means to effectively identify the evolutionary path forward even as competitors are coevolving (Vidgen and Bull, this volume). There are some researchers, for example Merali and Allen (this volume), who wonder out loud if any individual's comprehension or action can ever anticipate a successful evolutionary strategy. However, although this is an open question among researchers, it is, I believe, a settled assumption in business. Executive compensation would seem to imply a widely held (if somewhat optimistic) belief that individuals do guide organizations and can guide them through changing circumstances.

Complexity science implies that what executives are looking for are the unfolding situations that McKelvey (this volume) calls 'butterfly events'. By this reference, McKelvey refers to events, experiments with small beginnings that grow to have large scale effects. The term references a finding from a part of dynamical systems analysis called deterministic chaos that was originally identified by Lorenz (1972). The 'butterfly effect' refers to the possibility that the flick of a butterfly's wings in one part of the world might, under the right boundary conditions, cause a storm half way around the globe. This is possible by a characteristic of these systems called sensitivity to initial conditions (SIC).

Butterfly events, or what I call constructive deviations from the expected, reveal new information about the state space itself, and the organization's attractor cage. This information can then be used to enable the events to build upon themselves very rapidly (Lichtenstein, this volume), often causing impacts across scale as the emergence of new properties becomes evident (Goldstein, this volume). The effects of 'butterfly events' cross scale when the divergent elements of the experiment are 'scale free' and are characterized by power law relationships as Andriani and McKelvey (this volume) describe. In other words, the event might be observed at a level of coarse-graining that is relevant to a work group or a single retail store, or it might be observed at a scale that is relevant to an entire firm or industry (Maguire, this volume).

The invention of the microprocessor by Intel (Hazy, 2008a) is an example of this. Small businesses bought PCs to run spreadsheets, but large firms also saw workflows across whole departments change. Eventually the entire industrial economy was impacted by this change that crossed scale. The same was true of the Internet and the browser when they first appeared. Possible butterfly events in the present economy include the growth of Facebook and Twitter services, renewable energy concerns and tightening credit markets after the financial downturn that began in 2007 and the ensuing banking crisis (Posner, 2009). Butterfly events are important to small firms, like a Mom and Pop hardware store, and they are important to a large firm like The Home Depot. But when they first appear, they might very well be missed or underestimated. Missing or underestimating the relevance of these 'surprises' can be disastrous. Members of the executive management team of The Home Depot told me late in 2001 that they were being cautious with respect to changing their business model in response to the Internet. I don't know to what extent this decision drove their corporate performance, many other things happened including a change in senior management, but I did watch as their stock declined 30% over the 18 months beginning in January 2002. The Dow Jones Industrial Average (DJIA) was flat over that same period.

From a practical perspective, in order to understand where butterfly events might come from, and to recognize them when they arrive, information must be gathered, encoded and shared (Boisot, this volume). Conceptual models must be built and also shared to reflect both the individual's perspective and organization's potential (McKelvey, this volume). I would argue that dynamical systems models, like discounted cash flow analysis and business plans (Hazy et al., 2009, 2010), whether formal or informal, are needed to enable the thoughtful exploration of interdependent and interacting variables that cross scale. Guastello (2002, this volume) provides a good overview of this process from the psychology perspective of individuals within the organization. MacLean and MacIntosh (this volume) describe how work groups can engage problems and solve them in real time through action learning. Eisenhardt and Piezunka (this volume) and Baumann and Siggelkow (this volume) describe the implications of these events on a firm's strategic choices.

In all cases, the process involves a thoughtful but relentless testing of an organization's capabilities – its abilities in customer service, sales, treasury function, innovation, strategic partnering, etc. – against the changing needs of the coevolving (Vidgen and Bull, this volume) environment. In rapidly changing, or high velocity environments, rapid exchange with the environment is vital if the firm is to stay abreast of change and identify potential 'surprises' that might signal a butterfly event is happening. The goal is to reduce uncertainty and to roughly determine the shape of the forces that are influencing the organization across scale. The work of Andriani and McKelvey (this volume) on power-law science is an analytical approach that can be used to identify the presence of forces that cross scale.

So what does an enlightened manager do differently tomorrow? The short answer is to try things, but not just anything. One must try things that test the models that the organization's members are using to understand their own capabilities in the environment and then bring new information into the organization that validates or challenges key assumptions. Importantly, this process takes time and cannot be rushed. At the same time there is a point where additional information can no longer be gathered. This is a difficult point to identify, but when that time comes, the manager must decide what to do, and do it. This leads to the next and final New Rule.

New Rule #5: Recognize and reinforce larger scale patterns to ride waves of renewal

Gell-Mann (2002) cautions actors within organizations to remember to take a 'crude look at the whole' (p. 22). Acknowledge, if you will, that each player is only a part of a larger system and is generally only concerned with a partial, specialized perspective. Still, it is vital to bring the big picture into focus. Earlier in this volume, Eoyang describes the importance of recognizing patterns. But recognizing the pattern is not enough. To be actionable, the local genesis of these patterns must be identified in the context of what is happening locally and described in terms of the mechanisms that, along with forces in their environment, form the genesis of an emerging big picture. In other words, in complex human systems there is no getting around the link between what is emerging on a large scale (Goldstein, 2007, this volume) and what is happening as human beings interact with one another. These are the mechanisms that complexity science can bring to light for managers.

Although this realization presents its challenges, especially in light of our limited understanding today, it is also liberating. This is because it makes explicit the link between individual human action and large scale social, political and economic change. It opens the door to the possibility that, like local interactions, these large scale patterns across space and time can indeed be influenced by the choices and actions of individuals acting in the here and now. Nagging social problems such as health care reform (Zimmerman, this volume), resource limitations (Hazy et al., in press), and global warming all become problems which can be addressed systematically but also in the context of individual human action (Bankes, this volume).

The challenges for managers and for policy makers are threefold: (i) to uncover and to explore the information gained from the mechanisms that are operating locally but are also distributed widely, often with distinct local adaptations (Goldstein et al., 2010), across a diverse environment; (ii) to recognize patterns that might indicate a potential force that is impacting the organization across scale; and (iii) by modifying local mechanisms, to exert influence on the patterns that are unfolding even as these larger scale patterns also exert influence back onto the organization and its members. This is a formidable challenge to be sure, but because humans have well developed observation, modeling and communications capabilities, human beings are uniquely able to attempt this. Admittedly, however, success often remains elusive.

The broad impact of the Apple iPod, for example, can be used to illustrate what I mean here. Even without an exhaustive study of the case, for illustrative purposes one can quickly identify the most relevant locally operating mechanisms as: (i) People had to like the iPod product itself and its interaction with customers; (ii) stores had to agree to carry the iPod units and accessories for broad retail distribution; (iii) people had to find the iTunes website user-friendly; (iv) artist and publisher agreements had to be negotiated to enable songs to be posted legally; and finally, (v) an economic exchange had to occur to enable users to download songs in a way that supported the system from an economic perspective. These were local interaction mechanisms, often with locally adapted specific instantiations with their own peculiarities that together, in interaction, drove a social and economic phenomenon (Silberstang and Hazy, 2008).

All of these mechanisms were unfolding amid broader technological and social trends that included increased internet access, improved digital storage, widespread adoption of mobile phone and data services, a maturing techno-savvy population, and a period of uninterrupted economic prosperity. Most observers would agree that the team at Apple Computer managed this difficult complexity problem with considerable success. On the one hand, the wrong variations to any one of the mechanisms above might have doomed the emerging ecology. While on the other hand, failure to make the right changes along the way might also have doomed the project. Interestingly, Apple CEO Steve Jobs had arguably come out on the short side of a similar complexity face off in the 1980s. As Apple Computer navigated the emerging microprocessor marketplace, the firm refused to separate their operating system from their hardware platform. Splitting these two distinct loci of innovation during that period had enabled rapid adaptation by competitors like Microsoft, IBM and Intel. These firms, and not Apple, went on to shape that computer industry in the 1980s in the same way that Apple shaped the iPod marketplace in the 2000s (Linzmayer, 2004; Cruikshank, 2006). It seems that Steve Jobs, the CEO of Apple during both of these periods, learned his lesson from the 'PC wars' and changed his approach.

Ormerod (this volume) takes up this adaptation story at the macro scale with respect to economic systems in general and of innovation and strategy development within them in particular. His chapter in this volume is fundamentally about limitations, about the conditions under which individual human beings must act when confronting these emerging large-scale patterns. Where on the one hand complexity opens the door to human agency, Ormerod cautions that on the other hand, complexity also says that the door can never open much more than a crack. He points out that our capacity to comprehend this unfolding, and thus our ability to influence the same is limited by our collective history. Our only tools are those that our species has received through evolutionary selection, together with frozen accidents (Gell-Mann, 2002) and the luck of mutation, recombination, discovery and communication. This tool-kit does not provide anything that approximates an instruction manual. Richardson (this volume) places these limitations in a broad philosophical context raising this issue as a cautionary note for all science, indeed across all knowledge pursuits. But from a practical business perspective, once complexity is encountered and its fundamental character is acknowledged, one cannot think of innovation (Andriani, this volume) or strategy (Eisenhardt and Piezunka, this volume; Baumann and Siggelkow, this volume) in quite the same way.

What then is this last and grandest of the 'new rules'? How does one change the way one grapples with the 2009 restructuring of the once-great US Automobile manufacturer General Motors, or the troubled financial system in 2007–2008 (Posner, 2009), or for that matter the rapid growth of an Internet phenomenon like Twitter? In many ways this is the grand challenge of economic and business experience. It also has great meaning for me personally and is my *raison d'être* as a student of complexity science. I spent over 20 years with the US phone company AT&T which was never able to adapt to changing patterns on a large scale. With tens of billions of US dollars and market opportunities identical to those that spawned Microsoft, Apple, Cisco Systems and Google, the old AT&T could never find its way. (In late 2005, the old AT&T was acquired by SBC, Inc., a company that it had divested in 1984. The successor company was renamed 'AT&T'.) Why? And why do some companies, like Intel succeed? Complexity does help with this question. It points the way, but the road is not a 'simple' one. The five rules listed here are a good first step.

So what does an enlightened manager do differently tomorrow? Perhaps the most important lesson of all is that in today's complex world, leaders have to give up the illusion of control. Certain aspects of organizational life are certainly predictable, but these are often not the most interesting ones, nor the most lucrative. Sometimes the next big thing is embedded in exactly the distraction that just won't go away.

In 1996, I remember sitting in a top management team meeting at AT&T where my old company was deciding to sell one of its business units, AT&T Paradyne, because it wasn't aligned with the firm's strategy. This modem company had recently developed a new technology that supported Digital Subscriber Line (DSL) implementations. At the meeting, one of AT&T's top scientists dismissed DSL as 'an interesting transition technology' but not one that AT&T needed to worry about. After all, in the future everything would be connected by optical fiber, he reasoned. The firm went on to sell the business unit along with this technology to a private equity firm, the Texas Pacific Group (TPG) for $175M. TPG in turn monetized the asset over the next few years and earned a portfolio rate of return of over 100% for its investors. DSL is the technology that telephone companies still use today (in 2010) to bring Internet access into the homes of millions of Americans. Thirteen years and still going is a very long transition indeed, longer even than the time left for the old AT&T to exist as a stand alone company. Riding the wave of renewal is often the only path to survival.

CONCLUDING REMARKS

Having had many executive roles over more than two decades within some of the largest (and smallest) firms in the world, I was asked by the editors of this volume to reflect upon the contributions represented here and to comment on what they might mean to practicing managers. This challenge is reminiscent of a series of conversations I have had with old colleagues who are still senior executives at Global 500 firms. After I would tell them what I was learning about complexity as applied to human organizations, they would be intrigued, and they would unfailingly offer a kind smile, but it would be accompanied by a question like this: 'This is all quite interesting, but what does it tell me to do differently tomorrow?' This chapter has attempted to answer this question.

I do believe that an appreciation for complexity ideas deeply changes how one thinks about and acts within business organizations. This in turn changes what one should do every day as well. The insights developed in this volume are both about making meaning in a complex and changing world and about taking effective action within that world. They are about experiencing what is happening in a thoughtful and realistic manner and about making things happen that might otherwise never come to pass. They are about taking things as they come and also about making the world the place one wants it to be. But lasting change to the practice of management according to these new rules will not happen quickly.

In true complexity fashion, I will invoke recursion and brashly apply the conclusions of this chapter to its own potential. Applying rule #1, I observe that evolutionary change from traditional heroic leader and manager models to a complexity mindset (Marion and Uhl-Bien, this volume; Hazy et al., 2007) is likely to require a change in generations. Perhaps things won't really change until we dinosaurs die. Rule #2 highlights the inevitability of surprise. This all but guarantees that we will not know what works best until events play out for a while. Applying Rule #3's argument that improving one's organization is a forward-looking exercise, implies that the organization of the future will not simply be a better version of the past; it will be qualitatively different.

Rule #4 encourages active experimentation, a kind of trial-and-error process, to search for new approaches that, once perfected, will be more effective in the long run. New ideas must be protected and nurtured as they need time to develop and grow (Allen and Boulton, this volume). As the earlier discussion of fitness landscapes showed (Vidgen and Bull, this volume; Baumann and Siggelkow, this volume), it takes time for the new structures to be honed into efficient and replicable management practices and routines (Hodgson, this volume). In the end, a new way of thinking about and doing things will emerge, and this will eventually dominate management practice as the last rule, Rule #5 suggests. This new way will be embodied as management by these five new rules. Managers who catch the wave will become the role models for their generation, and for the generations that follow.

Today, most managers do not derive their personal organizing principles based on a complexity mindset. Rather, they remain locked in the design and push-to-fit mindset of the industrial age. It worked for a generation, but it doesn't work today. Those managers with the prescience to adopt the complexity paradigm will gradually do better than their peers. They will see things that others don't see, and they will try things that others cannot even comprehend. And some of these things will work. As more people adopt the new ways, these new practices will be imitated (with variation) and in the process, management practice according to these new rules will become ever better. Over time, those unable to adopt the new paradigm will drop away or die off.

I believe that the effective managers of the future will be doing five things differently than are even the very best leaders of today. The first two new rules describe how managers will think differently in the future. Rule #3 requires that managers both think and act differently, and the final two rules describe what successful managers, those who will rise to the top of their professions, will be doing differently than their peers. For practicing managers who are driven to invest the time to read this volume, its overarching lesson is that the future will be in the hands of those managers who realize that complexity is more than a metaphor. It is a new way forward. As a follower of this new way, you will be the first to see the unfolding patterns that are driving deep change. As the first to see, you will be in the very best position to engage and then to shape the emerging future as you and your organization rise with the tides of change, first by catching and then by riding, each successive wave of renewal.

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PART III

Interfaces

31

Nonlinear Dynamical Systems Applications to Psychology and Management

Stephen J. Guastello

THE BROAD LANDSCAPE OF NDS IN PSYCHOLOGY

This chapter surveys the recent developments in the application of nonlinear dynamical systems (NDS) theory to theoretical and practical problems encountered in psychology that are also relevant to management. For the benefit of non-psychologists, it is important to note that the scope of psychology is expansive. Introductory textbooks are typically organized around the following themes: brain physiology and behavior, psychophysics, sensation, perception, learning, memory, cognition, intelligence and mental measurement, development, social psychology, motivation and emotion, personality of normal range people, abnormal psychology, psychotherapy and counseling, and industrial-organizational psychology. At the other end of the professional spectrum, the largest professional organization for psychologists, the American Psychological Association, contains more than 50 topical interest groups in addition to its general membership core. The literature on NDS psychology reaches all the major areas of psychology and is growing rapidly (Guastello et al., 2009). For that reason it would be beneficial to focus on the broad themes that have the strongest support at present and that are most relevant to management.

COGNITIVE SCIENCE APPLICATIONS

Current thinking in NDS theory is that consciousness is an integrated process consisting of psychophysics and sensation processes, perception, cognition, learning, memory, and action. Although it has been convenient to think of these processes as separate entities, the separations are somewhat contrived. An incoming flow of stimuli is first encountered by the human processes of sensation and psychophysical transduction. Perception processes organize the incoming stimuli into recognizable wholes through combinations of learned regimes and innate capabilities. Cognition involves a wide range of processes by which the recognized patterns are compared, associated with information already in memory, transformed in simple or complicated ways, and organized into responses.

Learning involves one or more processes by which the individual organism acquires knowledge, skills, abilities, and adaptive responses. Memory pertains to how what is learned is organized and stored, and without which learning would be impossible. Psychomotor response – how the response is produced by the individual – is now considered part of an integrated cognition-action process (Shelhamer, 2009). Learning and creativity processes are considered in greater depth next.

Learning

Learning theory has implications for individual training and development, team building, and the so-called learning organization. Learning theory has undergone numerous developments in psychology in the past century. The major conceptual developments include trial and error learning, the learning curve, the concept of reinforcement, conditioned reflexes and associationism, operant conditioning and schedules of reinforcement, cognitive learning theory and cognitive maps, vicarious learning and imitation. Reinforcement, which proceeded from Thorndike's Law of Effect, depends on reactions from the environment, which in turn developed into an understanding of how information shapes behavior in lieu of actual rewards derived from attaining a behavioral objective.

A more recent regime is implicit learning theory (Seger, 1994), which focuses attention on things that are learned while the learner is trying more deliberately to learn something else. NDS has extended this principle to the explanation of work group coordination, making it a group learning phenomenon (Guastello and Guastello, 1998; Guastello et al., 2005a). Team members implicitly learn to coordinate with each other and entrain their behaviors to each other while engaging in a more explicit task learning objective. Coordination is considered in further depth later in this chapter.

The nonlinear dynamics of learning can follow one of two basic patterns depending on one's interest and emphasis. The first involves chaotic processes leading to self-organization. The learning curve is typically drawn as a smooth function. There is actually a lot of irregularity in the portion of the curve prior to the asymptote (Hoyert, 1992). The neurological explanation is that neural firing patterns are themselves chaotic in the early phases of learning while the brain is testing out possible synaptic pathways. Once learning has progressed sufficiently, the brain locks onto a particular pathway to use consistently (Skarda and Freeman, 1987; Minelli, 2009).

The second dynamic principle involves the cusp catastrophe model. If we extend the baseline of the learning curve (Figure 31.1, left) prior to the onset of the learning trials, two stable states are apparent; according to Frey and Sears (1978) hysteresis exists between learning and extinction curves cannot be explained otherwise. Different inflections in learning curves can be explained as a cusp bifurcation manifold (Guastello et al., 2005a) as shown in Figure 31.1 (right).

The cusp model for the learning process would be

$$dy/dt = y^3 - by - a \tag{1}$$

where control parameter a (asymmetry, governing proximity to the sudden jump) is the ability of a person or the number of learning trials, and control parameter b (bifurcation, size of the sudden jump) would be the difference between treatment and control groups, motivation, or differences in schedules of reinforcement, or any other variable that would contribute to making some learning curves stronger or steeper than others.

The cusp model is particularly good for training and program evaluation. If a statistical cusp effect turns out to be better than the next best alternative linear model it would denote all the features associated with a cusp model. Here the idea of *stable* end states adds a desirable feature to program evaluation: We want stable improvements to behavior targets, not simply statistically significant differences.

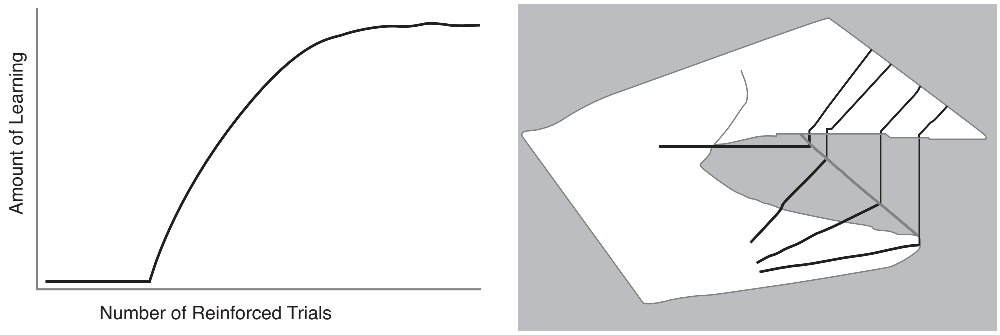

Figure 31.1 Typical learning curve (left) shown as a trajectory on a cusp catastrophe response surface (right). Adapted from Guastello et al. (2005a), with permission of the Society for Chaos Theory in Psychology and Life Sciences

'Stable' does not mean 'without variability', however. A bit of variability is necessary if it will ever be possible for the person, group, or organization to attain greater levels of performance (Abbott et al., 2005; Mayer-Kress et al., 2009). Figure 31.2 illustrates the dynamics of performance improvement. The person, group, or organization encounters a new task that cannot be readily assimilated into old or crystallized learning. With practice the new learning is attained, and the level of hysteresis across the cusp manifold increases with repeated new challenges.

Creative problem solving

Creativity is a complex phenomenon involving divergent thinking skills, some personality traits that are commonly associated with creative individuals across many professions, an environment rich in substantive and interpersonal resources, and cognitive style. Cognitive style is a combination of personality and cognition; it refers to how people might use their talents rather than the quantity of such talents. According to an early version of the 'chance-configuration' concept (Simonton, 1988), creative products are the result of a random idea generation process. Greater quantities of ideas are generated from enriched personal and professional environments. Idea elements recombine into configurations as part of the idea generation process. When the creative thinker latches on to a new configuration and explores it as a possible solution to a problem, a form of self-organization of the idea elements takes place.

In the context of NDS, however, the generation and recombination of idea elements is

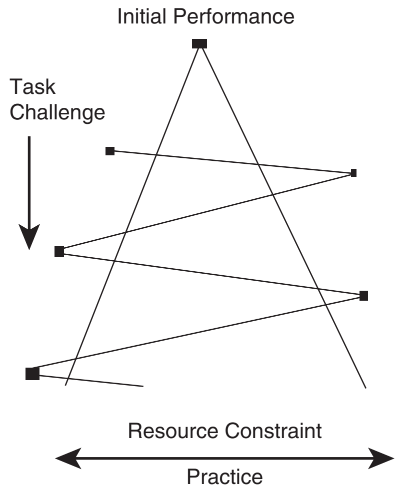

Figure 31.2 Periodic shifts in skill level appear as movements across a cusp manifold

chaotic rather than random. The self-organization of idea elements is largely a response to a chaotic system state. The idea elements, meanwhile, are generated by deterministic human systems, whether individually or in groups. The individuals filter out some ideas and attract others depending on their goals for problem solving. They also organize idea elements according to their own unique mental organization and experience; some of these mental organizations are shared with other people in the society with other problem solvers in the group, whereas other mental organizations are more unique. The process of idea generation retraces the paths that the individuals have mentally created already among idea elements, prior to any one particular problem-solving event (Guastello, 1995, 1998a).

The mushroom (parabolic umbilic) catastrophe was found to explain the dynamics of creative problem solving in groups who were working together in a real time experiment (Guastello, 1995). The response surface represents two simultaneous and interacting clusters of social interaction patterns. General Participation included information giving, asking questions, and statements of agreement with other people's ideas; it was found to be a bistable variable. Especially Creative Participation included statements that initiated courses of action for the group, elaboration of ideas, and rectifying intellectual conflicts; it displayed one stable state with instability at the high contribution end of the scale. Two of the four system control parameters, both of which were asymmetry variables, were occupied by personality traits. One cluster of traits distinguished high-production participants from low-production participants on the factor for general contributions. Assertiveness distinguished those who most often gave especially creative responses from others. The two bifurcation control parameters were overall group activity level, which captured a social dynamic, and the effect of particular experimental stimuli, which captured an environmental contribution. The news bulletins were introduced periodically as part of the game; they contained unexpected changes in the problem situation that should provoke an adaptive response from the players.

The mushroom structure itself was verified through a polynomial regression technique. In this case, a nonlinear regression technique was also used for estimating a Lyapunov exponent, which was positive and translated into a dimensionality of 5.46. This high dimensionality, which is also fractal, was an important observation because, according to the theory, chaos leads to self-organization, and as creative self-organized systems engender more instability, it would follow that creative problem solving groups are systems operating at the edge of chaos or far-from-equilibrium conditions.

Other studies have also explored whether computer-facilitated communication can enhance the group's overall level of production compared to the production of a collection of noninteracting individuals, so long as the group is large enough to produce a critical mass of ideas. Computer media can facilitate chaotic levels of idea production one would observe bursts of high and low idea production over time by either individuals or groups. Larger changes in production by individuals are associated with greater quantities of ideas that are produced by other group members in between two successive inputs from a particular person. These dynamics conform to the logistic map structure where the contributions by the other group members act as the control parameter (Guastello, 1995).

At the group level of analysis, greater productivity is associated with a relatively complex problem task, where the task can be broken down into subtopics. At that time the group members can work on any subtopic in any order they choose, go back and forth among the subtopics, and so on. In the actual groups studied (Guastello, 1998a), the number of active topics increased and decreased in a periodic fashion. The level of output by the group was chaotic overall, but it also showed periodic rises and drops in activation level in accordance with the change in the number of active topics. Thus the result, in the thinking of synergetics (Haken, 1984), is a coupled dynamic consisting of a periodic driver

$$A_2 = 0.75A_1 \exp(-0.36A_1) + 0.33 \qquad (2)$$

and a chaotic slave

$$Z_2 = \exp(0.25Z_1) + 0.43A_1 - 0.26C - 0.34 \qquad (3)$$

In Eqs (2) and (3), Z_1 represents group production levels can be observed depending on the topic that the group is working on (C); and A is the number of active discussion threads during the time interval of Z_1; time was measured in four-day periods. The exponent in Eq. (2) was negative, and the exponent in Eq. (3) was positive.

SOCIAL AND ORGANIZATIONAL PSYCHOLOGY

This group of topics includes social cognition, motivation, conflict, creative problem solving, group coordination, and leadership emergence. The theory related to motivation extends to a model for personnel selection and turnover, and an interpretation of motivational flow.

Motivation

Psychological theories of motivation have taken many forms over the years. Hunger and thirst predispose animals to behave as desired in learning experiments. The rat knows where the cheese is, however, we can leap quickly to expectancy theories of motivation whereby the decision maker chooses behavior options that will produce the desired expected reward levels. There is also a theory of equity, in which the agent takes action to restore or maintain equity with other agents.

Another important theme that pervades many social and organizational theories of motivation is the distinction between intrinsic and extrinsic motivation. Extrinsic motivation and extrinsic reward describe situations where the agent receives reward from an outside source. It contrasts with intrinsic motivation, where the agent receives reward, usually intangible, from the activity itself. Examples of intrinsic motivation would include the motives for achievement, affiliation, and power.

Physiological motivation consists of only one form, which is arousal. Arousal originates in the reticular formation of the brain, transfers to the thalamus, and transfers again to the cortical areas where it is interpreted. The same essential process applies to emotion as well.

The butterfly catastrophe model of motivation in organizations draws together many of the previously-known dynamics affecting personnel selection and training, motivation, and work performance, absenteeism, and turnover (Guastello, 1981, 1987, 1995). The principles of several motivational theories are represented in the model. The butterfly catastrophe model consists of three stable states of performance and four control parameters. The three stable states are (a) high performance and initiative, low absenteeism, and low probability of turnover; (b) adequate performance, absenteeism is not out of the norm, and low probability of turnover; (c) performance is inadequate, or absenteeism is excessive, turnover is likely by either voluntary or involuntary means. The four control parameters are ability (asymmetry), extrinsic motivation (bifurcation), intrinsic motivation (swallowtail), and a management climate that tolerates individual differences and encourages intrinsic motivation to dominate over extrinsic motivation (butterfly). The gradients on the butterfly responses surface that run between the stability points and the point of degenerate singularity are interpretable as approach and avoidance gradients in motivation and conflict theory.

Personnel selection

Although all parts of the model, including the butterfly structure itself, have been empirically verified, it should be noted that some practical applications of this model may involve only subsets of the butterfly dynamics. One useful case in point is the cusp catastrophe model for personnel selection and turnover. Conventional wisdom treats the two phenomena separately and attempts to explain them with separate lines of reasoning. The cusp theory (Guastello, 2002) treats them as an integrated process wherein the two stable states are (a) hired and working, and (b) not hired or terminated. The performance and turnover are measured on the same scale where persons not hired or terminated are given the performance level of zero. Ability measurements would comprise the asymmetry parameter, and motivational indicators such as career interests would comprise the bifurcation parameter.

In an illustrative example (Guastello, 2002), the cusp was used to explain and predict turnover among US Air Force recruits during their first term of enlistment. Recruits completed a battery of ability and career interest measures when they first enlisted. Performance-turnover measurements were taken at six-month intervals. After time lapses of 24 and 30 months, the cusp model predicted performance and turnover more accurately than the next best linear model. Note here that for any dynamical process, it is necessary to give the system enough time for the dynamics to transpire. Short term changes can be locally linear even though the global process is nonlinear. The reasons are topological not statistical (Wiggins, 1988): any short distance along a curve can be well approximated by a linear model.

Motivational flow

If one were to define a more complex dynamical field, such as having many tasks to choose from, the dynamics become progressively more complicated. Flow is a motivational state of total immersion in a task brought in, or sustained by skill demands and challenges. It is a state where time and the outside world seems to disappear while the individual is working, particularly in creative endeavors (Csikszentmihalyi, 1990). Individuals who change tasks throughout the day are likely to spend more time with tasks that engender a high level of flow, rather than a low level of flow.

In a dynamical study of flow, Guastello et al. (1999) asked 24 subjects to keep a diary of daily events for a week, along with indicators of skills and challenges that were involved, and analyzed the time series for any inherent nonlinear dynamics. Three clusters of people were identified: Flow Type A showed slightly negative correlations between time spent on tasks and ratings of flow, low temporal stability (low R^2 for the linear comparison model), and a low R^2 for the nonlinear exponential model. Flow Type A appears to change tasks in short cycles with little regard for flow and is possibly caught in a life style where task selection is governed by external forces. Flow Type B also showed a negative time-flow correlation, high temporal stability, and relatively high nonlinearity. Flow Type B also appears to experience high external control over task selection, but with the difference that some tasks produce greater flow than others, unlike Type A. Flow Type C displayed high time-flow correlations, low temporal stability, and high nonlinearity. Flow Type C showed differential levels of flow with different tasks, but involvement periods were relatively long and dependent on the flow level for the task. Thus two control parameters appeared to be operating: internally or externally governed task selection and the range of flow levels associated with tasks.

Navarro et al. (2007) asked 20 people to keep a motivation log for four weeks. Participants periodically recorded their motivation for the task at hand, self-efficacy, and instrumentality of the task for achieving personal goals. They found substantial differences in stability versus turbulence in the time series across the 20 people and the three measurements. As a rule, self-efficacy beliefs were relatively stable over time, while motivation and instrumentality were much more volatile.

In a subsequent study (Ceja and Navarro, 2008) participants provided ratings of the same three variables plus others involving challenges and skills at random intervals for 21 days, 6 samples per day. All variables showed deterministic chaos over time, as determined by visual recurrence analysis and comparisons with surrogate data. It was not entirely clear what contributed to the levels of volatility in the latter two studies, although the irregular time intervals could have been responsible.

Conflict

The available studies on conflict and NDS involve agent-based models, the pathways to chaos as pathways to conflict, or the cusp catastrophe once again as an explanation for approach and avoidance gradients or group polarization. Agent-based models illustrate how individuals working in their own self-interest produce self-organized systems as they interact with other individuals. Self-organized systems often manifest sudden and discontinuous changes that are recognized as catastrophes or phase shifts (Guastello, 2002). Competition-cooperation dynamics are often inherent in those dynamics (Maynard-Smith, 1982; Axelrod, 1984). They are also inherent in group performance dynamics which are considered in a later section of this chapter.

There are three basic pathways by which a system can become chaotic. The first is an application of the three-body problem. Figure 31.3 shows a more complicated example (from Borges and Guastello, 1996; Guastello, 2002, 2009a) of an attractor field with three attractors (A1, A2, A3) of different strengths. The points labeled S are saddles, or compromise points between each pair of competing attractors. The opportunity for conflict here is that, if a point enters the field, it is pulled in different directions in an unpredictable way, as denoted by the tangled thread. A partial solution to the conflict between two attractors, which represent two arguable positions on an issue, would define

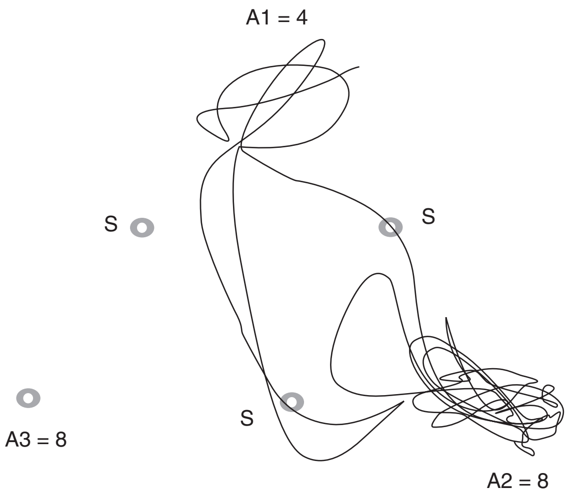

Figure 31.3 Path of a point in a field of three attractors and three saddles. From Guastello (2009a), reprinted with permission of ISCE Publishing

saddles that could attract points from two directions. In the simulation, a point indicating the position of the solution entered the field in the neighborhood of A1, visited two of the compromise positions, and landed on A2. The implication, nonetheless, is that bilateral agreements are not going to resolve any conflict if there are three or more interest groups involved; A3 received virtually no attention even though it was as strong as A2. The odds of people changing their preferences for possible solutions often increases as the number of options and the number of interest groups increases. In fact, chaos is more or less guaranteed if there are four participants and four options (Rand, 1978).

The second pathway involves coupled oscillators. Imagine a set of three pendula that are pinjointed together at the ends. When Pendulum 1 oscillates, Pendulum 2 moves faster and its motion pattern becomes more complex than strictly periodic, and Pendulum 3 swings chaotically. The opportunity for conflict can be found in a coupled system involving, for instance, three organizations in a supply chain. Pendulum 3 does not like being jerked around, and probably cannot function well with all the entropy or unpredictability associated with the motion of the system it is experiencing. In human terms, the uncertainty associated with entropy is equivalent to the experience of risk, which the people or groups that reside later in the chain would like to control.

The third pathway to chaos involves the logistic map bifurcation where a control parameter that increases the level of entropy in the system. When the value of a control parameter passes a critical value, the system oscillates instead of remaining stable. As the value increases further, the oscillations become more complex, and eventually the system goes into chaos. The bifurcation model was a popular concept in organizational development (Michaels, 1989; Guastello et al., 1995; Guastello, 2002). At low values of the control parameter, the system is initially stable (Period 1). Pressure to change (control parameter) has no effect on the system's behavior until the control parameter exceeds a critical threshold. At that point the system oscillates between its old behavior pattern and a new one (Period 2). In the period-doubling regime we would observe the system making complex shifts among multiple behavior patterns. When the system enters chaos (Period 3), the communication and work flows become very inconsistent from moment to moment, or event to event. At this stage the system can self-organize into a new stable pattern and regain its stability by using the new pattern. On the one hand, the bifurcation mechanism explains how to unravel an otherwise stable system in order to make some needed changes. It also characterizes a group exploring ideas for change that could be opposites of each other. Eventually one would need to reverse the control parameter to bring the system back to stability.

Organizational development scenarios often present conflict opportunities because the pressure to change points in one direction while resistance leads to actions that prevent or nullify the change initiative. Although the organizational change agents imagine that the new processes that they are touting are inherently good, that is not necessarily something to be assumed. The complex adaptive system naturally prevents invasive changes from taking root.

Polarization is often connected to conflict in groups, either as a starting point, or as a high-water mark of the group's activities. Groups often discuss their ideas, plans, and attitudes and find they have differences of opinion. In cases where the participants are not too emotionally involved at a personal level, they often find midpoints or compromise positions that are agreeable to most participants. If the topic or attitude target is 'important', however, continued discussion will lead to polarization of group members, rather than compromise. Latane (1996) expressed the dynamics as a cusp catastrophe model. There are two stable states (attractors). The group begins at the unstable point (a saddle) on the surface and then splits into distinctive poles if the importance of the attitude is high, and does not polarize for less important attitudes.

In a related theme, Vallacher et al. (2010) characterized intractable conflict states themselves are single attractors. The attractors are formed by combinations of attitudes, goals, and more importantly, interaction patterns among the conflicting parties. If a situation is inherently complex there are some elements that are salient and closely linked to some of the other elements, but could also be some elements that are not linked or attended to as well as they should be linked. The unattended elements self-organize into a latent attractor that presents conflict with the more manifest attractor. The boilerplate solution to conflict is to break up some of the interaction patterns, thus creating entropy and a search for a new attractor where elements are connected differently, perhaps in a more integrated fashion, and presumably life would be better.

Leadership emergence

The rugged landscape model of self-organization offers a cogent explanation for organizational phenomena, particularly where strategic management is involved (McKelvey, 1999). The rugged landscape model of self-organization also explains how leaders emerge from a leaderless group, and the possible ways in which their emergence could take form (Guastello et al., 1998b, 2007a, b; Zaror and Guastello, 2000; Guastello et al., 2005b). The group activity selected for study involved a complex creative problem solving task. Once presented with the task and an hour (of experimental time) to complete it, numerous verbal interactions transpire among group members. These local interactions culminate in the eventual self-organization of the group such that the role of a general leader emerges along with several other, more specific roles.

The formation of roles would constitute fitness peaks, which denote relative fitness, local stability, and clusters of similar subspecies with regard to shared adaptive traits. The probability density function that is associated with the swallowtail catastrophe model (Eq. (4), Figure 31.4) describes the distribution of people into unstable and locally stable social roles. The swallowtail catastrophe structure contains a response surface of discontinuous events, or qualitatively different outcomes, such that there are two stable states, with a minor antimode between them, an unstable state, and a major antimode separating the unstable state from the two stable ones:

$$\mathrm{Pdf}(z) = \xi \exp\,(\theta_1 z^5 + \theta_2 z^4 + \theta_3 c z^3 + \theta_4 b z^2 + \theta_5 a z) \qquad (4)$$

In Eq. (4), z is the extent to which members of the group endorse a particular group

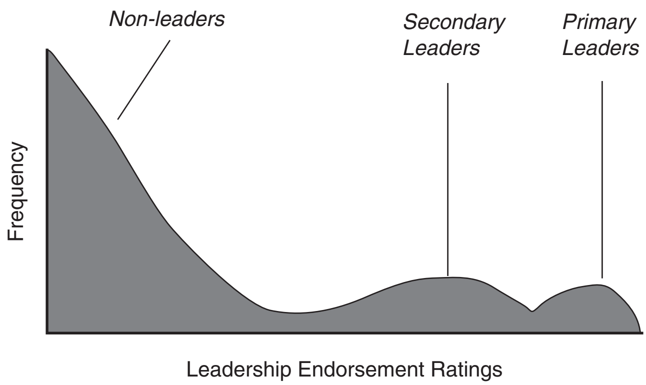

Figure 31.4 Swallowtail catastrophe distribution of leadership ratings after a leadership emergence process. From Guastello (2007b), reprinted with permission of the American Psychological Association

Table 31.1 Summary of results from leadership emergence studies with the swallowtail catastrophe model*

Type of group	*Asymmetry*	*Bifurcation*	*Swallowtail*
Creative problem solving	General participation and control of the conversation; including gate-keeping, initiating, following, harmonizing, facilitating the ideas of others, task orientation, consideration of other players' interests, concern for solution quality.	Giving information, creative ideas, competitive behavior, concern for solution quality.	Unknown
Production	Tension reduction, including harmonizing, giving information, goal realism.	Creative and task control, controlling the conversation.	Unknown
Coordination-intensive	General participation and control of the conversation; including gatekeeping, initiating, following, creative ideas, facilitating the ideas of others.	Verbal vs. non-verbal working conditions	Task control
Emergency response	Wide-range competitive behavior against adversary, controlling the moves of the team, helped other members make good moves, asked questions, contributed information, boosted team morale.	Group size	Group performance

* Summarized from Guastello et al. (2005b), Guastello and Bond (2007a), Guastello (2010a).

member as the leader; *a, b,* and *c* are control parameters; ξ is a constant that maintains unit density; and θ_i are nonlinear regression weights. The model requires three control parameters. Research to date has investigated the nature of the control variables, which vary in their content depending on what type of group is involved, e.g. creative problem solving, production, and coordination-intensive groups. One control parameter (*a*) distinguishes all leaders from non-leaders. The second (*b*) controls the extent to which the leaders stabilize into either primary or secondary roles. The third (*c*) distinguishes the primary from the secondary leaders. Table 31.1 contains a summary of those findings.

Work group coordination

Coordination occurs when group members make the same or compatible responses at the right time for optimal production. Contrary to conventional thinking, there is more than one type of coordination in game theory. As with any type of game, individuals make decisions based on the utilities associated with the options. Prisoner's Dilemma involves choices between cooperation and competition. The Stag Hunt game involves choices between joining the group (to hunt stag) and going off on one's own (to hunt rabbits). A potential negative outcome in Stag Hunt is social loafing or the free rider syndrome.

The Intersection game requires group members to take the correct actions in the correct sequence, and to figure out the correct sequence, similar to what occurs in a four-way stop intersection. If the drivers correctly perceive the turn-taking system adopted by the preceding drivers and follow the sequence, then all cars pass through the intersection in a minimum amount of time with the lowest odds of a collision. In a real-life intersection, any of several possible rule systems could be adopted by the drivers, and each driver approaching the intersection needs to recognize the strategy that is actually in effect, and then make the correct move. If a car tries to go through the intersection out of turn, then an accident could occur, or at the very least, other players would need to revert to ad lib turn-taking to untangle the confusion at the intersection.

The process of group coordination involves the development of nonverbal communication links among the participants. These links evolve with repeated practice with each other. The evolution of the links is essentially a self-organization process. Furthermore, the basic process of coordination is non-hierarchical, meaning that a leader, who usually contributes task structuring activities of some sort, is not required. This state of affairs is not unlike the flocking of birds, herds of beasts, or schools of fish, which operate without leaders.

The results of Intersection game experiments to date show that if the experimental task is not excessively difficult, the group will display a coordination learning curve (Guastello and Guastello, 1998). The coordination acquired during one task session will transfer to the learning and performance curve of a second task. If the task is too difficult, self-organization will not be complete, and the time series of coordination data will be chaotic. A coordinated group can withstand changes in personnel up to a point before coordination breaks down (Guastello et al., 2005b). Verbalization enhances performance to some extent, but not necessarily the level of leadership emergence (Guastello and Bond, 2007a).

Coordination and hierarchies

Coordination does not *require* leaders, and the mainstay of game theory experiments in economics are conducted without leaders or even talking between the participants (Friedman, 1994). One premise of evolutionary game theory is that a large volume of simple bilateral interactions produces global results for the social system. Individuals can adopt hierarchical rules or strategies (*oligarchic reaction functions*) such as tit-for-tat. Again, leaders and hierarchical relationships are not necessary (which explains some of game theory's popularity with neo-classical economists). Another key point is that the relationship between long-run equilibria (*evolutionarily stable states*) and the utilities within single-shot games is not always consistent.

The forms of coordination observed in non-hierarchical non-human species are not leader–follower relationships. A flock of birds will stick together on the basis of only three rules: following the general heading of the flock, stick close to the flock, and do not crash into flock mates. The goose at the vertex of a V formation is not the leader; they rotate positions. A school of fish stick together in much the same way; they have a rule of motion whereby they exchange positions from the outside to the inside of the school and out again as a means of hedging against predators. Wilson (1975) suggested that leadership occurs in non-hierarchical groups when one member of the flock detects a predator first, even if by virtue of keener sight or smell, or a more advantageous location for detecting signals. The animal that moves first moves the group. The member of the flock who has keener senses, or flies fastest, moves the group most often and appears most similar to anthropomorphic leaders.

Southeast Asian fireflies will start the evening by flickering quasi-randomly, but after a few hours they synchronize into a coordinated pulse throughout the forest. *Synchronicity* can be produced even in non-living systems with only minimum requirements – two coupled oscillators, a feedback channel between them, and a control parameter that speeds up the oscillations (Strogatz, 2003). The oscillators synchronize when they speed up fast enough. The principle also has been demonstrated with electrical circuits and mechanical clocks. Leadership is irrelevant to circuits and clocks.

None of the above negates the principle that leaders can *emerge* in coordination-intensive human task groups that begin without leaders. Members that do emerge as leaders exhibit a wide range of behaviors that are useful to the group who can communicate freely and exert control over the task. Thus they become the hub of communication (information flow) in both verbal and nonverbal modalities (Guastello and Bond, 2007b).

So what do leaders actually do that is constructive? Leaders can invent options for goals and means of attaining them. Leaders can alter perceptions of utilities, and a good sense of reality is critical here. Leaders can become the hub of communication. Leaders can set the pace for the group's work.

There is some agreement (Guastello, 2008; Van Vugt et al., 2008), nonetheless, that leadership is not necessary for many types of tasks, and that constituents can adopt strategies to influence the behavior of leaders. Nonlinear dynamics offers a more direct path to the same conclusions, however, and with additional insights: Emergent group structures and performance patterns can form strictly from the bottom up with or without a supervenience principle whereby the upper level dominates the actions of the lower level. It is overly simplistic to think that the upper level dominates the lower and that is the end of the story. Experimental evidence shows that the antics of the lower level can destabilize performance at the upper level, and the skill of managing a workflow within a hierarchy is not widely shared (Guastello, 2002: Chapter 10). Even in the most benign case where people are just trying to do their jobs, management can be very scattered in its efforts to stabilize a work flow. At present it is not clear how much of the skill for managing this form of chaos could be trainable, or something to be studied in a personnel selection context.

FUTURE DIRECTIONS

Empirical verification is always an issue in psychology generally, not only in NDS applications. Dooley (2009) observed that empirical studies of NDS in organizational behavior that involve real data are rare, particularly in comparison to the number of well-reasoned concept pieces that have been written. The logistic map model for organizational change, for the times it has been cited as a prototype of the change process, has not received any direct empirical study.

Empirical analysis is nowhere near impossible as the studies captured in this chapter have illustrated. One does *not* need a godzillion data points to assess a fractal dimension or any other important dynamical indicator, nor is it necessary to test a myriad dynamical models devised by mathematicians to determine a viable model for real-world data (Gregson and Guastello, 2005; Guastello, 2009b; Guastello and Liebovitch, 2009). Techniques built on the generic characteristics of chaos, self-organization and other dynamics, such as entropy measurements and structural statistical equations, serve the purposes well.

By the same token, many of the theoretical models in this chapter have been empirically demonstrated only once, although a few have received more attention. It would appear that significant and practical advances can be made by building on NDS models that are known already concerning learning, creative problem solving, motivation, personnel selection, leadership emergence, work group coordination, and work flows in hierarchies. The material on conflict in organizations is relatively new, however. The principles of pathways to chaos are internally rigorous, yet it would be beneficial to see how they play out during real-world conflict resolution projects.

At the theoretical level of development, the concept of the complex adaptive system is central to our understanding organizations. Psychology has begun to consider what adaptive behavior could look like (Pulakos et al., 2000). There is a sense that learning and creative behavior are both involved. It would follow that a highly functional theory could result from building on the known dynamics of learning and creativity, and make greater use of NDS indicators of turbulence and adaptation such as the Lyapunov exponent (Guastello, 2010b).

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32

The Value in Between: Organizations as Adapting and Evolving Networks

César A. Hidalgo

INTRODUCTION

An F-22 fighter costs around USD$150 million and weighs around 20,000 kg. per unit of weight, an F-22 costs close to USD$7,500 per kilogram or USD$3,400 a pound. Compare this to a kilogram of gold which is currently (February 2010) priced at around USD$34,000, or a kilogram of silver which costs around USD$500. A kilogram of F-22 is expensive, yet as scrap metal, the exact same airplane will not sell for much. If I divide a lump of gold or silver into pieces, the value of each one of these pieces, compared to the whole, will be identical to the fraction *that* its weight, volume, or size represents relative to the whole. This is certainly not true for an F-22 fighter, since the value of a sophisticated good, such as a computer, a car or an F-22, comes from the precise way in which its parts are assembled, rather than from the materials from which they are made. In such cases we can say that the value of these goods is in the network that connects the different parts, and in the networks that were able to get these parts together. The value is *in between*, in the links, rather than in the nodes. A copper wire is more valuable when connecting two people on the phone, or a power plant with a city. A computer keyboard is more valuable when connected to a computer and this to a monitor and the right type of electricity. In all kinds of systems, the value is in the network, so if we want to understand what value is and how it emerges, we need ways to adequately quantify the structure of the networks that products are, and the networks that make these products come true.

Firms and institutions are not only large collections of individuals. They are networks of individuals that interact sometimes through hierarchies, but mostly, despite them. The ability of a firm to be productive depends not only on the talents of its employees, but largely on the way in which they interact. The value of an organization or institution, just like that of an F-22, lies largely in the network that sits between its members. The networks that define an organization, however, are not necessarily the organizational charts we see pinned down on an organization meeting room, but rather the networks that emerge from the informal interactions that occur between an organization's members. Two firms, with the exact same organizational chart, can have diverging fates. Can we say the same about two organizations characterized by similar informal network structures?

Some evidence supporting the hypothesis that the structure of an organization's informal social network is related to that organization's performance is exemplified, for instance, by the recent work of Kidane and Gloor (Kidane and Gloor, 2007). Kidane and Gloor looked at correlations between the creativity, performance and network structure of open source software development teams and found that more centralized groups performed better, in the sense that they were able to fix more bugs, than less centralized groups. They also found that the creativity of groups, measured as the number of new features a group came up with and implemented during a given time period, was smaller for more centralized groups. All in all, Kidane and Gloor's findings suggest that trade-offs between a team's performance and creativity could be reflected in, or mediated by, the structure of the social networks they define.

Oscillations between centralized and decentralized network structures have been shown empirically to be a defining characteristic of creative teams. Waber et al. (2007), used sociometric badges (a technology we will discuss later) to measure the interactions between different teams in a German bank and found that the oscillation between more and less centralized network structures was characteristic of teams charged with the design of new marketing campaigns, yet it did not occur in teams that were not required to perform creative tasks.

These examples illustrate how details in the structure of an organization's informal social network are related to an organization's performance. These examples also suggest that, in order to adapt, organizations need to be flexible, as the ability of organizational networks to morph into different configurations could be the key allowing organizations to perform properly and survive over the long run. To properly adapt, however, organizations need to achieve a certain degree of self-awareness, they need to see themselves as the networks they are, a task that is extremely difficult to achieve for organizations involving more than 30 or 40 individuals.

Manufacturing companies are well aware of the need to understand their own functioning and have learned to adapt their production processes by paying close attention to their mistakes. The key behind the success of the Toyota Production System (TPS), or Lean Production, is its ability to turn manufacturing errors into learning experiences (Spear, 2009). Companies that operate under lean production use errors to learn about, and improve, their production process. This is the direct opposite of mass production, which tries to avoid the propagation of errors in the assembly line by accumulating large inventories at several points of the manufacturing process. Mass production was successful at lowering production costs. Yet, lower costs came at a high price. The price of low costs was adaptability. Mass production traded off production costs for the ability of a company to learn about its own weaknesses. Adaptability, however, is a price that no organization can afford.

Taking the ideas of the TPS, or Lean Production, to knowledge based organizations, however, may not be completely straight forward. This is because most assembly line errors have well defined physical symptoms, such as the jamming of a machine or inconsistencies in delivery times. The 'cogs' of many private organizations and government institutions, however, are people, and the assembly lines running across government and service organizations are social networks. Any attempt to apply TPS to these government and service organizations, therefore, requires, in some form or another, an increase in the knowledge that an organization has regarding its own social interactions.

Network science, as a combination of sensing methods and analytical techniques, can help organizations become more self-aware. Organizations that understand their own networks will likely have a better chance adapting, as knowledge regarding their current configuration can help the design, evaluation and performance of working teams. Ultimately, this self-awareness can improve the ability of an organization to adapt and survive. But in order to look at themselves, organizations need to be able to see not only the performance of their members, but the ways in which these are connected. To understand an organization is to understand its network dynamics. Work places are intricate social and political environments that can collectively perform tasks that no single individual can. Organizations are giant super-organisms with a market-like consciousness that emerges from the interactions of several, information deprived individuals. The question is then, can network science help awaken this giant? Can network science take the consciousness of the super-organisms into the next level?

In the next couple of sections we review some of the most standard literature on Network Science created during the last decade. Both of these sections describe, in general terms, some of the measures most commonly used to quantify the structure of networks. In the sections that follow we will review literature on studies that use these measures, together with other techniques, to understand the structure and organization of real world social networks. For a more in-depth review of Network Science and its applications to other scientific fields we suggest looking at the following reviews (Albert and Barabási, 2002; Newman, 2003; Borner et al., 2007). For more information about organization sensing technologies we suggest Pentland (2008) as a good starting point.

NETWORK STRUCTURE AT THE TURN OF THE CENTURY

Network visualizations can be both inspiring and intimidating. Good network visualizations can be extremely informative while at the same time being aesthetically appealing. Yet, for some people, the 'high-tech' look of network visualizations can sometimes be intimidating. It is important to remember that networks are simply collections of nodes and links, dots and lines, and hence the most basic measures used to characterize their structure are rather simple.

We can begin characterizing the structure of a network by looking at measures that capture information about a node and their immediate neighbors (a.k.a. local measures). The most basic of these measures is the *degree* of a node, which is usually denoted by k and represents the number of links that a node has. One can think of a node's degree as the number of friends a person has. In general, it is helpful to think about any network using social analogies. The degree of a node is the simplest of a class of measures called 'centrality measures' which are measures created to quantify the importance of a node in the network. Other centrality measures are, for example, *closeness centrality* (Bavelas, 1950), which tells us what is the average distance between a given node in the network and all other nodes and *betweenness centrality* (Freeman, 1977), which tells us how many of the shortest paths connecting different pairs of nodes in the network go through a given node.

Another local measure that is widely used is a node's *clustering coefficient*, which measures the density of triangles in which a node is involved. The clustering coefficient can be thought as the probability that two friends of a node are also friends themselves. Mathematically, the *clustering coefficient* of a node can be defined as:

$$C = 2\Delta/k(k-1) \qquad (1)$$

where Δ is the number of triangles in which a node is involved and the $k(k-1)/2$ factor represents the total number of triangles that the k neighbors of that node can potentially participate in, which is equal to the combinatorial k choose 2.

There are also measures that are used to characterize the structure of a network by capturing global information, meaning that these are measures containing information that involves, either all, or at least the majority of the nodes in a network. One important measure of this kind is the *degree distribution*, which is a histogram of the degree of all the nodes in the network.

The degree distribution has been shown to be a defining characteristic of a network. In 1999 László Barabási and Reka Albert showed that various networks were characterized by a power-law degree distribution (Barabási and Albert, 1999) – which mathematically means that the probability that a node has k links is proportional to $k^{-\gamma}$ where γ is a constant with a value that has been empirically determined to lie in most cases in the range of $2 < \gamma < 3$ (Albert and Barabási, 2002). In more qualitative terms, a power-law degree distribution tells us that there are a few nodes in the network that have a number of connections comparable to the total number of links in the network, while most other nodes have only a small number of connections. Nodes with a disproportionately large number of connections are known as *hubs*, and their existence carry important dynamical consequences for the network (Barabási Linked). Barabási and Albert coined the term scale-free network to refer to this class of networks.

Barabási and Albert also introduced a simple model that could generate scale-free networks (Barabási and Albert, 1999). The Barabási–Albert, or BA model, can generate a scale-free network by allowing the network to grow through the addition of nodes that come into the network with a set number of links. An essential ingredient of the BA model is that new nodes are more likely to connect to nodes which are already highly connected. This mechanism, known as preferential attachment and discovered previously by Yule (Yule 1940s) and Price (Price 1970s), is a simple way to generate models with power-law degree distributions. Yule and Price, however, never used it to simulate the structure of a network.

The finding that many networks from the most diverse kinds are characterized by broad degree distributions, such as power-laws, was extremely revolutionary for Network Science. This simple finding was not expected from the theoretical models of networks available at that time, which assumed that connections occurred randomly, and therefore, expected networks to be characterized by Poisson or exponentially decaying degree distributions. Until that time, many theoretical models of networks were built on the Erdos and Renyi, or ER model (Erdos and Renyi, 1959), developed by the mathematicians Paul Erdos and Alfred Renyi. The ER model was created for abstract reasons, and therefore, was not an accurate approximation to most real world networks.

The distinction between networks with a broad degree distribution and random networks is more than a statistical curiosity. Scale-free networks behave qualitatively different than random networks, for example, when we remove nodes from them. A well studied fact is that the fraction of nodes that remain part of the largest connected component of a scale-free network is comparable to the total number of nodes in the network, even after randomly removing a substantial number of nodes (Albert et al., 2000; Cohen et al., 2000). This property is not shared by random networks which break up into several components after the removal of a comparatively small number of nodes (Albert et al., 2000). Yet, when instead of removing nodes randomly we do so in a targeted manner, by removing first the nodes with the highest degree and then work our way down to low degree nodes, scale-free networks break up more quickly than random networks (Albert et al., 2000; Cohen et al., 2001). Hence scale-free networks are relatively more robust to the failure of random nodes than random networks, but at the same time are considerably more susceptible to fall apart under targeted attacks.

Another property that separates scale-free networks from random networks is the way in which they affect the spread of quantities, such as information or infectious diseases. Pastor-Satorras and Vespignani showed that scale-free networks have a vanishing epidemic threshold (Pastor-Satorras and Vespignani, 2001), meaning that in a scale free network viruses will always have a chance to spread. This was a shocking result for the field of epidemiology which until that time was dominated by models unable to incorporate the relevance of network structure into the spreading dynamics. In recent years, the importance of scale-free and non-scale-free networks in the diffusion of different quantities has become increasingly more relevant. Different examples where network diffusion studies have captured an important amount of attention include (i) the diffusion of medically relevant conditions, such as obesity (Christakis and Fowler, 2007) and smoking (Christakis and Fowler, 2008), (ii) studies on the role of the World Airline Network in the spread of infectious diseases (Colizza et al., 2006a; Colizza et al., 2007) and (iii) the study of the evolution of countries productive structures constrained by the network of similarity between products (Hidalgo et al., 2007; Hidalgo and Hausmann, 2008).

In addition to the degree, clustering and degree distribution, an important variable that has been widely used to characterize the structure of networks is the average distance between a pair of nodes, known as the *average path length* $<l>$. For a long time the intuition that any person in the world could reach any other person through a short chain of acquaintances had been prevalent in popular culture, as exemplified for example by Karinthy's popular story 'Chains' and by the Broadway play 'Six Degrees of Separation' (Karinthy, 1929; Barabási, 2003). Random networks, as those studied by Erdos and Renyi, are also characterized by short average path lengths. Yet, the random networks studied by Erdos and Renyi have a clustering coefficient that is inversely proportional to the number of nodes in them ($C \sim 1/N$) (Albert and Barabási, 2002), and is therefore extremely small for networks composed by more than a few tens of nodes. Hence, Erdos and Renyi random networks cannot explain that social networks are simultaneously characterized by high levels of clustering (the friends of a person are relatively likely to be friends themselves) and short average path lengths.

In 1998 Watts and Strogatz showed that networks could have, simultaneously, a high level of clustering and a short average path length (Watts and Strogatz, 1998). In their landmark publication Watts and Strogatz illustrated their finding by using a circular lattice, which was characterized by high clustering and high average path length, and showed that after rewiring only a small number of links the average path length of their lattice could be brought down to that of a random network. Moreover, they showed that the clustering of the network remained relatively high even after a substantial number of links had been rewired. Watts and Strogatz found that in the parameter space of their model (given by the probability of randomly rewiring a link), there was a large region in which networks can exhibit both, high clustering and short average path lengths. Networks sharing both of these properties became known as Small-World networks, while the particular network model introduced in Watts and Strogatz's paper became known as the Watts and Strogatz network (Watts and Strogatz, 1998).

GOING DEEPER INTO NETWORK STRUCTURE

The works of Réka Albert, László Barabási, Duncan Watts and Steve Strogatz, together with the availability of large network datasets, sparked a landslide of publications that have since been concerned with the study of the structure and dynamics of networks of the most diverse kinds.

Other structural measures that have been used to characterize the structure of different networks are measures of *degree-degree correlations*, which look at whether nodes with a relatively high or low number of connections are more likely to connect with nodes with a relatively high or low number of connections. In other words, do hubs tend to connect to hubs?

Degree-degree correlations have been studied with variations by several different authors. One of the first examples of the study of degree correlations is exemplified by the work of Pastor-Satorras, Vazquez and Vespignani (Pastor-Satorras et al., 2001). Pastor-Satorras et al. used data on the Internet at the autonomous system level (simply put these are connections between different ISPs) to show that, in that particular network, hubs tend to connect to low degree nodes. Newman took this idea further by creating a measure of *assortativity*, which is positive for networks in which hubs are likely to connect to other hubs and negative for networks in which hubs tend to connect to low degree nodes (Newman, 2002). Newman applied his assortativity measure to several collaboration networks (networks in which the coauthors of a scientific paper are connected), a few biological networks (such as protein–protein interactions), some technological networks (such as the Internet and the WWW) and a few network models. His analysis found that social networks exhibited assortative behavior (hubs tend to connect to hubs) whereas technological and biological networks were more likely to show the opposite, disssaortative behavior, in which hubs tend to connect to low degree nodes (Newman and Park, 2003).

Another group that measured the degree–degree correlations of networks was Sergei Maslov and Kim Sneppen, who noticed that the degree distribution of a network imposed an important constraint in the degree–degree correlations of a network (Maslov and Sneppen, 2002). The idea was that in networks with a heterogeneous degree distribution, such as scale-free networks, hubs will on average appear to connect to low degree nodes. This is because there are simply not enough hubs for a hub to connect to, and therefore hubs have to connect mostly to low degree nodes. This constraint will also be expressed as a relatively high number of connections between low degree nodes and hubs. Measures that do not consider this effect will ultimately be biased towards finding a disassortative behavior in networks with a broad degree distribution, such as scale-free networks.

Maslov and Sneppen proposed measuring degree correlations by comparing the observed level of connectivity between nodes of given degrees with those of randomized networks. In their randomized networks every node has the same number of links as in the original network, and hence the network conserves its degree distribution (Maslov and Sneppen, 2002). By comparing the degree–degree correlations of the original network with that of the randomized network Maslov and Sneppen introduced a way to measure statistical properties of a network while controlling for the connectivity of its nodes. This idea was pushed further by Colizza et al. in a study in which they introduce the rich club coefficient as a way to quantify such behavior (Colizza et al., 2006b).

Another area of intense study in network science is that of *community structure*. Measures on networks' community structure attempt to formalize the observation that in some networks there are groups of nodes that belong to densely connected groups, or communities, which themselves are only sparsely connected to other communities. Measures on the community structure of networks look to answer questions such as: Are there communities in a given network? And if so, how strong is the community structure exhibited in that network? How many communities are there? And, to which community or communities does a node belong?

In recent years several methods to assign nodes to communities have been proposed. All of these methods are based on different heuristics developed to capture the intuition behind the idea of communities. One example is the method introduced by Girvan and Newman (Girvan and Newman, 2002), in which they iteratively remove links of a network according to the link's betweenness centrality (Freeman, 1977). The idea behind this method is that links that lie between communities will tend to have high values of betweenness centrality, as the links that lie between communities will likely be in the shortest paths connecting nodes from different communities. Hence, by removing these links iteratively, Girvan and Newman found a way to break up the network into different communities. Soon after publishing this method Girvan and Newman and Girvan introduced a *modularity* measure that could be used to determine the number of links that upon removal would break up the network into the most adequate set of communities (Newman and Girvan, 2004). Using the modularity measure links could be removed iteratively in search for a modularity maximum, which indicated the most adequate partition of the network into communities according to the authors' method.

An alternative definition of communities was proposed by Palla, Derenyi, Farkas and Vicsek, who noticed that previously proposed community finding methods forced each node to a single community. Palla et al. (2005) pointed out that an individual could belong to more than one community and proposed an algorithm that could be used to assign an individual to several communities. The algorithm proposed by Palla et al. consisted of taking a fully connected subgraph, or clique, and 'rotating' it inside the network. All nodes that could be reached by the same clique were assigned to the same community. Yet, a node could potentially be reached by cliques rotating in different subsets of the network, as a node could be the nexus between several cliques. This allowed this algorithm to assign nodes to several communities.

During recent years, several other methods for community detection have been proposed including methods that can be used to detect communities in bipartite networks (Lehmann et al., 2008), methods to detect communities based on local information (Bagrow and Bollt, 2005; Clauset, 2005), Bayesian methods (Hofman and Wiggins, 2008) and spectral methods (Newman, 2006). Ultimately all of these methods can be used to understand the natural groups that emerge within an organization despite and because of bureaucratic constraints.

THE STRUCTURE OF LARGE SCALE SOCIAL NETWORKS

To understand organizational networks we must complement statistical measures, such as the ones described in the previous sections, with technologies that can help us sense social interactions. After all, constraints to our understanding of social networks can arise from the coverage and reliability of the data available as much as from the limitation of our analytical methods.

In the past few years, an important number of studies have looked at different aspects of social networks by looking at the logs that record people's interactions occurring through different communication channels. These scientific developments have been fueled by the rapid advancement of information and communication technologies that have resulted in a large increase in the number of interaction channels that people use to communicate with each other. Some of these new channels include, but are not limited to (i) asynchronous channels, such as email, text-messages, blogging, microblogging (e.g. Twitter), social networking sites (e.g. Facebook), and video posts (e.g. Youtube), and (ii) synchronous channels, such as instant messaging, video calls and mobile phones. The massive adoption of these technologies has opened the opportunity to study the networks of interactions that are expressed through each one of these channels, as all of these technologies have the ability to record users' interactions, either for billing, reliability purposes or both.

During the last five years, anonymized mobile phone records have been used to look at the structure and dynamics of large social networks in an attempt to understand the statistical properties of the ways in which large collections of people self-organize. By looking at the mobile call patterns of a few million individuals, Onnela et al. (2007) showed empirically that the links located in the more densely connected parts of the mobile phone network tended to be stronger, in the sense that the total amount of time used in those calls was longer, than the links located between groups. The idea that links between groups tended to be weaker than those within groups had been already proposed some decades ago by the sociologist Mark Granovetter (Granovetter, 1973). Onnela et al.'s contribution, however, took this idea further by using the empirically determined network structure to quantify how this particular property of social networks limits the diffusion of information across it.

Mobile phone records have also been used to study the temporal stability of social interactions. In a recent study, Hidalgo and Rodriguez-Sickert (2008) used a year's worth of mobile phone records to study how the persistence of a social tie, measured as the probability of observing a link when looking at the network during a certain time window, was related to different network properties. The authors found that the persistence of links was positively correlated with the density of the network, measured using the clustering coefficient, and the reciprocity of interactions, determined by looking at links in which calls were initiated by both parties. They also found that there was a tradeoff between the degree of an individual and the average persistence of that individual's ties (people with more social ties tended to have a smaller fraction of persistent ties). Yet, this tradeoff was found only to be partial, as Hidalgo and Rodriguez-Sickert showed more connected individuals tended to have a larger number of persistent social connections, despite the fact that as a fraction of the total number of ties, the fraction of persistent ties was smaller for more connected individuals.

The dynamics of social groups has also been studied by using mobile phone records. In a recent paper Palla et al. used a year's worth of mobile phone data, together with their community finding algorithm, to show that large social groups that survived for relatively long periods of time tended to exchange a large fraction of members. This was contrary to lasting small social groups, which tended to survive as long as the memberships remained (Palla et al., 2007).

Studies like these are important because they illustrate that it is possible to characterize individuals by looking at the structure and dynamics of their social interactions. Moreover, they show that in social networks different aspects of the network structure are strongly correlated, suggesting that the network structure surrounding an individual defines categories that can be used to understand the different kind of individuals that are part of society. The structure of the social network surrounding an individual is likely affected by that individual's personality, as it is an objective measure of how that individual is embedded in society. Hence, by combining log data with network analysis we can gain access to aspects of an individual that we would not be able to reach with demographic or socioeconomic data (Hidalgo and Rodriguez-Sickert, 2008). For example, demographic and socioeconomic data would not be useful to differentiate between two neighbors living in the same suburb, having similar income, family composition, level of education and age, but having extremely different personalities. Because of the aforementioned reasons, measures extracted from social network data can give us access to a more relevant quantitative picture of an individual, as the structure of the social network surrounding an individual is likely related to that individual's personality more than its neighborhood, gender or age.

From a business standpoint, the characterization of an individual that can be extracted from its social network can be extremely relevant. In recent years there has been evidence showing that marketing segmentation based on the structure of an individual's social network can produce better targets, measured by comparing the adoption rate of targets chosen using social network structure and more traditional marketing segmentation methods. Better marketing segmentation methods are beneficial for companies and customers, as improving marketing segmentation strategies reduces the cost of marketing efforts incurred by companies and at the same time diminishes the amount of unwanted marketing material handed off to customers.

The structure of an individual's social network can also be a good predictor of future behavior (Hidalgo and Rodriguez-Sickert, 2008). This makes accurate quantitative information about an individual social network extremely valuable for companies whose businesses require anticipating individual behavior, such as, for example, the renewal of a service contract or the adoption of new services in the future. A good example of this is recent work by Dasgupta et al. (2008), in which social ties were used to accurately predict the churn of mobile phone users.

Automatically collected data has also been used to study the communication patterns defined by small networks of individuals within an organization. For example, Aral et al. (2009) studied the communication patterns of an executive recruiting firm and found that multitasking individuals tend to prefer asynchronous communication channels (in particular email) over synchronous communication channels (such as phone) (Aral et al., 2009). They also found an inverted-U shape relationship between multitasking and productivity, meaning that multitasking increases productivity until a certain point after which additional tasks had a negative effect in productivity.

Email networks have also been used to study organizations. Probably the most well studied email dataset is Enron's email database (Shetty and Adibi, 2004; Keila and Skillicorn, 2005). An interesting example of the type of information stored in Enron's emails is exemplified by the work of Collingsworth and Menezes. In a recent study, Collingsworth and Menezes found that the number of cliques in Enron's email network (subsets of the network in which everyone is connected to everyone else) jumped from 100 to almost 800 one month before the December 2001 collapse (Collingsworth and Menezes, 2009). The author's interpretation of their findings was that, one month before the collapse, people in the organization began talking directly to people they felt comfortable with and stopped sharing information more widely. Collingsworth and Menezes' study shows how changes in an organization's email network can be indicative of its internal processes.

HONEST LINKS

Recent technological developments have also opened new opportunities for the study of face-to-face interactions. A particularly exciting body of research in this area, spearheaded by the Human Dynamics Lab at MIT, combines the development of 'reality mining' technology, which are devices designed specially to measure personal interactions, with signal processing, machine learning, psychological theories and real life experiments, to create the most comprehensive quantitative picture of face to face interactions to date.

During several years the Human Dynamics Laboratory, led by Alex (Sandy) Pentland, has been exploring the limits of wearable computing technology and its ability to objectively sense social interactions. Through a series of experiments, Pentland's group has been able to show that it is possible to quantify several aspects of human interactions by analyzing data collected from wearable devices that record the location, sound, acceleration and direction of those who wear them.

In their most recent incarnations, these 'sociometers' have been incorporated into small badges that can be integrated with current ID tags or have been developed as software, rather than as hardware solutions, that can be incorporated into mobile phones (Eagle and Pentland, 2006).

One of the striking aspects of this research is its proven ability to quantify the non-verbal aspects of human face to face interactions, which have been shown to be highly predictive of the outcome of interpersonal exchanges of the most diverse kinds. Pentland suggests that the information value of this 'Honest Signals' comes from the fact that they are processed unconsciously and that they emerge from our brain structure and biology, and therefore, they are hard to fake (Pentland, 2008). This makes this non-verbal signal more likely to be honest than the signaling produced by more conscious decisions, such as the clothes we wear and the cars we drive. In other words, the Human Dynamics Lab at MIT has been able to scientifically separate the information content of the things we say and of how we say them.

These sociometric techniques have been used to study pairwise social interactions as well as the dynamics of small networks of individuals. At the pairwise level, honest signals have been shown to be good predictors of the outcome of different types of negotiations. For example, by using these techniques in salary negotiations Curhan and Pentland were able to predict 30% of the variance in individual outcomes by examining a thin slice of data consisting of the first 5 minutes of the negotiation (Curhan and Pentland, 2007). Another example in which these sociometric techniques have been shown to be highly predictive is in predicting the matches that occur at speed dating events (Madan and Pentland, 2006). Speed dating is a matchmaking activity in which individuals have short interviews with a large number of potential partners and secretly indicate their preference for any of them at the end of the event. After all 'dates' have taken place the organizers of the event provide contact information to those pairs of individuals who have expressed mutual interest. Madan and Pentland showed that the combination of two female honest signals: high levels of activity and variable emphasis, were highly predictive of the decision of individuals to trade contact information (Madan and Pentland, 2006). They also found that males were able to read females quite accurately, as men were more likely to report an interest for woman who also reported interest in them, according to both sociometric technology and speed dating records.

While there are several interesting studies that use sociometers to relate honest signals with different types of interactions, from an organizational perspective the most interesting examples are the ones concentrating on the dynamics of groups of individuals.

Some of these studies are complementary to Bales' Interaction Process Analysis (IPA) (Bales, 1950; Bales and Strodtbeck, 1951), which is a method used to classify the interactions that happen in a group based on the type of behaviors that the members of a group adopt towards each other. Sociometers have been used to accurately classify the different roles undertaken by different individuals in a small group, helping automate IPA, a task that until now could only be performed by a trained psychologist. IPA has been shown to predict the outcome of group decision making, including problems such as groupthinking and polarization (De Waal, 2005). For example, if two people in a group happen to take the *attacking role*, decisions tend to be more polarized. On the other hand, if there is only one *protagonist* in the group, a typical outcome is that everyone follows the leader without exploring the entire set of options and potential pitfalls of the decision proposed by the leader. Sociometers are now being used to create real time feedback systems that can help keep groups on track.

During the last years, the Human Dynamics Lab at MIT began collaborating with large firms such as Hitachi (Baker, 2009). Hence, sociometers could soon enter the workplace, either as consumer products or as part of a new organization consulting and management standard that relies heavily on information about the interactions of an organization's members. The test that organizational sciences will pose to sociometric and other technologies will not be a test of adoption, but rather a test of survival. Ultimately, these technologies should enhance the survival probability of those organizations who adopt them. As the survival of organizations will be the one that determines whether network science becomes a frozen accident (Crick, 1968) in the evolution of management strategies or if it will be selected out until a future rediscovery.

FINAL THOUGHTS

Organizations are networks formed by heterogeneous groups of individuals that accomplish tasks that no single individual can. Like a soccer team or an orchestra, organizations are complex super-organisms whose performance depends on the interaction between the individuals that make up the organization, as well as on the structure of the networks that emerges from these interactions. Organizations, however, are networks that exist within networks. Since firms and institutions are networks that operate in environments that are formed by thousands of other organizations, firms and institutions can be seen as nodes in a large network of organizations themselves. Organizations are networks embedded in other networks and their survival depends as much on their internal structure as on the position they hold in their networked environments.

The ability for these super-organisms to adapt, however, will depend on the level of 'consciousness' that they can achieve. Self-awareness can be seen as the ability of an organization to understand its limitations and how to overcome them. Awareness is about being conscious about what is going on and where you are standing, for both individuals and for organizations. All organizations do have some sense of self-awareness, which comes from their ability to answer questions such as: What can they achieve using only their internal resources? Do they know if they can do it so competitively? And in the case they do not, would they be able to restructure its internal networks to a configuration that could help them solve this problem? Self-awareness is, for individuals and organizations, related to the ability of assessing relatively quickly and accurately one's own position in the larger picture, understanding the role that you are playing and on the implications of such role in relation to others. Can network science improve the ability of an organization to understand where it stands? Moreover, can network science improve the ability of an organization to answer questions about the environment in which the organization is embedded?

After all, the success and survival of an organization depends on its business ecosystem, and on its position within it. Organizations are part of complex economies which are formed by institutions and firms of the most diverse kinds. In complex economies value emerges from the interaction between these different organizations, together with other private and public inputs (Hidalgo and Hausmann, 2009). Ultimately, one of the goals of network science is to help this larger super-organism to wake up and become better at what it already does quite well, which is to divide up labor and generate prosperity. One step in this direction is to help organizations become more adaptable; as it could well be that an emergent property of an economy which is formed by more adaptable organizations is an overall system that is not only more adaptable, but rather, more evolvable.

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33

The Use of Complexity for Policy Exploration

Steven Bankes

INTRODUCTION

Policy decisions, whether made by government agencies, for profit companies, or individuals, typically concern systems that are both complex and open. There are special situations involving systems with a small number of agents where game theory can be informative and others where large numbers of effectively equivalent agents can be described in the statistical aggregate. However, most problems involve the middle ground where issues of complexity are important. Policy effects ramify through multiple iterated decisions, each a nonlinear function of perceived circumstances, where decisions by individual human agents can occasionally tip outcomes. And, public policy mostly deals with open systems that have no fixed simple boundaries. Economic realities can affect political processes, and in turn be affected by environmental, cultural, technological, and military developments. Policy systems are composed of individuals whose identities, ideas and social networks are undergoing constant change. In being complex and open, policy systems usually defy closed form analysis and reliable prediction.

Indeed, policy problems are frequently 'wicked problems' in the sense of Rittel and Webber (1973). This means that not only must policy be adaptive to cope with deep uncertainty and changing circumstance, but the analytic structures used to understand policy problems are context dependent and in need of adaptive response as policy coevolves with the systems being managed.

As a consequence, insights and tools from the complexity sciences have the potential to be very helpful for policy analysis. While heuristic advice derived from complexity science has the potential to be useful for at least some situations, this chapter focuses on using computational models to support policy exploration for decision making. We will consider first the possible advantages and dangers of using complexity inspired computer models for policy analysis and argue for the use of large numbers of modeling experiments to compensate for the deep uncertainty that policy must contend with. Methods for exploring parameters vs. non-parametric alternatives are discussed. Next, a series of aspects of exploratory analysis are discussed:

- Exploring Alternative Policies
- Exploring Uncertainties

- Joint Exploration of Policies and Uncertainties (Robust Decision Methods)
- Exploration of Values and Sources of Information
- Iterative and Interactive Exploration

The chapter concludes with a discussion of future challenges and research directions. While the focus of this chapter is policy analysis, model exploration through computational experimentation is a very general technique for complexity science. Consequently, much of what is described here actually has much greater applicability. Through the course of this discussion, a number of terms are introduced that may be novel for some readers. Table 33.1 provides a Glossary of terms that can be consulted for clarification.

THE ROLE OF COMPLEXITY IN POLICY ANALYSIS

The crafting of policy is an ancient art, with heuristics and compiled wisdom long predating the advent of the computer. Scientific policy analysis and associated computer modeling can improve the ability of decision makers to utilize data and knowledge in crafting policy, but they can produce as much harm as benefit if we fail to appreciate the complexity of the systems involved. Unwise policy actions can result from attributing simple causes to the symptoms of a problem or overconfidence in the predictive powers of a model. Direct actions taken based on assumptions of linear relationships and simple causal models are prone to produce unintended side effects. An example of such blowback is reported in Walters (1997). Here undesirable changes in the ecosystem of the Florida Bay were attributed to decreased freshwater flow, resulting in an increase in salinity. However, policy actions that succeeded in increasing freshwater delivery created new problems through turbidity plumes that decreased light penetration and inhibited growth, completely overshadowing intended benefits. Similarly, economic analyses that neglect political realities, or rational actor calculations that ignore cultural factors can lead to costly errors.

The advent of complexity science provides an important counter-weight for the universal human tendency to underestimate both uncertainty and complexity, and consequently to put inordinate faith in forecasts and simplistic policy prescriptions. Metaphors from the complexity sciences, including tipping points, adaptive landscapes, criticality, and co-evolution, have enriched policy discussions and provided a means to better appreciate the complexity of policy systems and to seek robust, adaptive, and contextually sensitive solutions.

Complexity science is facilitated by computer simulation modeling, which brings both opportunities and challenges to policy science. The use of computer models for decision analysis is still relatively new (a few decades experience), and the use of computer simulation is extremely novel for most problem areas. Computational studies of social systems can bring new insights that can inform policy. And computational social science is emerging to be a novel approach to understanding social systems (Carley, 1995; Epstein and Axtell, 1966; Axelrod, 1997a,b; Prietula and Carley, 1998; Gilbert and Troitzsch, 1999; Epstein, 2007). Conversely, a wide variety of complexity related computational social science studies are relevant to or were inspired by a policy question. Examples include models of advertising (Farrell, 1998), group dynamics (Carley, 1991), traffic and road planning (Nagel and Rasmussen, 1994; Burmeister et al., 1997), military combat (Ilachinski, 1997), epidemiology (Carley et al., 2006), financial markets (Bak et al., 1996; Arthur et al., 1997; Darley and Outkin, 2007), cultural dynamics (Axelrod, 1997a,b), political revolutions (Kuran, 1989), segregation (Schelling, 1971), city planning (Ishida, 2002), and command and control (Bonabeau et al., 2003).

Computer modeling provides an opportunity to combine disparate sources of knowledge and data, incorporate multiple phenomena, and illuminate tradeoffs among

Table 33.1 Glossary

Abductive Reasoning: 'Abduction … consists of examining a mass of facts and in allowing these facts to suggest a theory' (Peirce, 1933: 205). Abduction, is an 'inference to the best explanation' (Harman, 1965). In contrast to induction, abduction uses all available data to generate coherent patterns (Hanson, 1958). In the context of the exploratory approach advocated in this paper, abduction can be generalized to mean discovering (possibly multiple) plausible explanations consistent with available information. In decision making contexts this could include either discovering plausible decisions or plausible future scenarios given a decision.

Alternative Models. More than one model may plausibly represent what is known about a given problem, and ideally multiple alternative models would be tested as part of any policy analysis. As model construction is generally quite labor intensive, multiple alternative models are available only for problems that have gotten significant attention, notably climate and weather forecasting models.

Base Case. A base case is a single special case used to anchor excursions over alternative inputs (cases) for a computer model. Typically it is thought of as the best estimate case, and excursions are used to estimate the variability of model response around this case. The use of base cases is becoming archaic as the ability to run large numbers of cases is increasingly commonplace.

Coevolution is a concept from evolutionary biology, where for example predator and prey species evolve in parallel. Similarly, coevolutionary methods search in parallel across sets of possible solutions and challenges. These methods can be very powerful in focusing computation on those challenges which are most difficult for the leading solution candidates. (See for example Hillis, 1991.) In the context of this chapter, this is applied to searching for robust policies by in parallel seeking scenarios that are worst cases for the leading candidate policy recommendations.

Data Farming is the practice of creating a design of experiments for a given model, running all the modeling cases in the design (possibly on parallel computers) and analyzing the results.

Design of Experiments is a concept drawn from statistics, originally devised to support the design of physical experiments, where for example in medicine one might systematically vary treatments, and the demographic character of test subjects. Such algorithms can be applied to designing computational experiments as well. Full factorial and Latin Hypercube designs are examples of experimental designs that have been frequently used to create structured lists of computational experiments for data farming purposes.

Exploratory Modeling is a term for the general practice of exploring across alternative models or alternative cases (inputs) for a single model in search of insight to inform a decision. This is in contrast to the practice of using an experimentally validated model to make predictions. Exploratory modeling includes as proper subsets the concepts of Exploratory Analysis (exploration of inputs to a single fixed model) and Data Farming (structured exploratory analysis utilizing statistical design of modeling experiments and statistical analysis of modeling results).

Extreme Modeling is a term innovated for this chapter. Extreme programming is a term used to characterize programming methods emphasizing rapid agile development of computer applications through frequent iterations of development, testing, evaluation and modification. It is associated with Web 2.0 development and is often thought of as creating applications that are constantly being revised (perpetual beta). In analogy, this chapter speculates that future complexity modeling practice will be embedded in the environment being modeled, and that the models will be perpetually in flux.

Full Factorial Designs are methods for design of experiments that create a grid of points across the input variables. For example, if there are two inputs X and Y, with ranges [0, 10], then a 2×3 design would combine two levels of X (0, 10) and three levels of Y (0, 5, 10), to create six sample points: (0, 0), (0, 5), (0, 10), (10, 0), (10, 5), (10, 10). Full factorial designs require a total number of cases that grow geometrically with the dimensionality of the space. They are thus useful only for models with a small number of inputs.

Inequality Constraints are constraints that can be used to filter data or guide case generation where one quantity is required to be greater than (or less than) another. For example, in an environmental remediation model, one might only be interested in cases where environmental standards are met, or conversely might want to focus on failure cases where they are not.

Latin Hypercube Designs (LHDs) are experimental designs that are very useful for high dimensional models with large numbers of inputs. For a number of experiments (N) that are desired, N levels are created for each input, and these N values randomly permuted. LHDs are space filling, and the N sample points will be uniformly dense for any projection, such as one creating a two-dimensional point cloud. The data from the experiments can be used to analyze variance, or create a surrogate model that interpolates among the points (a response surface model). These latter analysis steps are facilitated if the sampling of the inputs is uncorrelated. This is equivalent to requiring that the vectors of values for any two variables have a zero dot product, producing an Orthogonal Latin Hypercube Design (OLHD). As the number of inputs grows, finding an OLHD can become computationally taxing. Consequently, Nearly-Orthogonal Latin Hypercube Designs (NOLHDs) where the correlation between variables is small are frequently used.

Table 33.1 (*Contd.*)

Level Sets are sets of points in the input space for a model for which an output of the model has a specific value or level. For example, contour plots display level sets of geographic locations that have a specific altitude. For nonlinear models, level sets can be non-convex, and not simply connected. The geometry of level sets is one way to portray the response surface of a model.

Model Cases. A case for a given model is specified by the list of values for the inputs to the model, and results in a list of values for its outputs. A case can be thought of as a point in the space of model inputs, that has associated values for the model outputs.

Model Uncertainty. For most policy systems, our knowledge of causal relationships is imperfect, meaning that multiple alternative models can plausibly represent dynamic relationships. This can be assessed in part by testing alternative models.

Pace Layered. The concept of pace layering was first introduced by Stewart Brand in the context of the life history of buildings, with the observation that over time some architectural details change rapidly, while others are more stable. Subsequently, it has been observed that in many natural and artificial systems change happens across a wide range of time scales. For example, in economic systems, prices change at time scales of seconds to days, companies are founded on a time scale of months and years, industries arise on the time scale of decades, and infrastructure change can involve time scales of centuries. This chapter hypothesizes that complexity modeling will eventually display similar pace layered properties.

Parallel Computation. Many options for running multiple model cases simultaneously (in parallel) exist including: single machines with multi-core chips, computational clusters (linked networks of computers) and cloud computing (multiple machines accessed through the Internet).

Parametric Uncertainty is uncertainty associated with input parameters of a model. Exploration over parametric uncertainty is much more readily accomplished than for uncertainty not associated with parameter values, which may be called structural uncertainty, model uncertainty, or non-parametric uncertainty.

Response Surfaces are mathematical objects defined by the behavior of a model. A given model output can be thought of as an elevation defined for each point in the space of possible inputs. This surface or terrain can be explored by sampling from the input space and running the corresponding cases. For non-linear complex models, the response surface can be much more rugged (with multiple peaks) than is true for simple models.

Response Surface Models fit a surface to a database of model results to create a surrogate model that is faster to execute and evaluate.

Robust Decision Methods are means of seeking decision options that perform adequately across the broadest possible range of uncertainty, in contrast with optimization methods that seek to maximize the value of outcomes given a best estimate case or probability distribution.

Scenario Discovery is the problem of discovering scenarios in the output (response surface) of a model. In the scenario planning literature, a scenario is a group of possible futures that share salient qualitative properties. A bridge between this literature and computational (model based) planning methods is made possible by defining scenarios as qualitatively similar regions in model input space. If the outcome of interest is profits, for example, the high profit scenarios will be the peaks in the profit response surface of the model in question. Applying classifier algorithms to data bases of model results is one option for discovering scenarios.

Space of Alternatives. Alternative cases, alternative futures, and alternative policies can often be structured by a topology with an associated way to measure distances between alternatives, creating a space. Structuring alternatives as a space is a useful analytic tool, enabling in particular search and visualization.

Spiral Process is an approach to development that emphasizes iteration as opposed to a linear sequence of steps. A linear process involving sequentially specification, construction, testing, and use, can be converted to a spiral by performing this sequence multiple times, with each spiral being an elaboration on the product of the previous spiral.

Trees, Lattices, and Graphs. Alternatives that are not numeric may still be related to one another, and this relationship can be used to identify nearby alternatives, facilitating search and analysis. For example individuals in a population can be related to others by being members of the same family, or the same profession. Neighborhoods are located in cities, cities in counties, counties in states. Such a web of relationships form a mathematical object called a graph or a network. Some graphs have important special properties. Graphs without cycles are called trees. Relationships such as part–whole that are transitive are said to structure collections as lattices. Such special properties allow more powerful means of exploring the collections of alternatives.

multiple values or goals. Modeling representations pioneered by the complexity community such as agent-based modeling provide a means to reason about the implications of classes of knowledge (such as that regarding cultural patterns of individual decision and action) that heretofore had little influence on policy modeling.

The significant limits on our ability to accurately predict the future behavior of complex systems presents novel challenges in the rigorous application of complexity modeling in policy settings. Models that can predict the outcome of choices are clearly very useful to support decisions. It is less clear to a casual audience how to utilize models that cannot reliably predict outcomes. Combined with other sources of concern with computer models, this has presented a significant barrier to using computer simulations for policy analysis. In order for complexity models to be helpful, they must both be a vehicle for informing policy makers of salient information, and be exploited in ways that are congruent with human reasoning and existing policy systems. Models can usefully provide insights that would otherwise not be available, even when they cannot be used as prediction tools. This requires building suitable models that capture salient information, and exploring their implications in a manner that provides useful insights into the policy problem.

The incorporation of complex computer models into policy analysis has potential hazards. Policy problems frequently involve political realities where multiple factions press for policies that serve narrow interests. Because policy systems typically are deeply uncertain, multiple models can plausibly serve to explain observed behavior, creating the real possibility that politically expedient choices can be promoted by choosing models that imply desired conclusions. When the models involved are the mental models of stakeholders, traditional political heuristics can accommodate the biases inherent in model proponency, but computer models can serve to obscure the logical basis for policy arguments and can give a scientific veneer to biased analyses. In particular, the biases introduced through unstated assumptions can lead to naïve inference about the actual state of knowledge about the policy issues at hand and suggest policy options that are insufficiently robust to uncertainty.

Whenever computer models are used in policy analyses, there is a natural tendency to ascribe predictive power to the computationally envisioned future. While predictive accuracy is a very powerful standard for assessing model quality (confusingly often referred to as model validation) for policy systems, the intersection between those situations that where prediction is possible and those where policies can make a difference is typically empty. This is because it is usually only for time scales where human agency can have no effect that prediction is possible. Prediction is possible for where the dynamics of the system create a ballistic trajectory where no action can affect the outcome, like a car that has already gone over a cliff. But in such situations prediction is of limited value. On the other hand, unless one is the only driver on the road, if there is time to avoid the collision, the actual outcome depends not only on one's own actions but those of other drivers. And so, in such a circumstance, accurately predicting the final outcome is not possible. Thus, the situations where our knowledge can best help to steer outcomes are principally those where the outcome is in doubt. For policy analysis purposes, we must often concern ourselves with models that can support valid inference about the implications of policy choices even though specific quantitative predictions may not be reliable.

While models of complex policy systems frequently cannot be relied on to predict the future, they can still serve a useful role as part of a human–machine collaboration, where models extend the ability of policy analysts and decision makers to envision the implications of available knowledge, posited scenarios, and available policy options. In short, models will often find their most powerful use not as devices to predict, but rather as a means to explore the implications of alternative policies and alternative plausible scenarios (Bankes, 1993).

Growing hardware capabilities make aggressive exploration of alternative decisions and future scenarios increasingly feasible. Computational experiments conducted for exploration can be conducted in parallel, and so the techniques of policy exploration can benefit greatly from the increasing availability of parallel computing resources, ranging from the ubiquitous deployment of multi-core chips, to cluster machines, and grid and cloud computing (see Glossary). For many models of interest, there is no barrier to routine use of millions of computational experiments to inform a policy choice. This presents the opportunity of assisting decision makers in considering a much wider range of uncertainty and future possibility than is currently possible. Properly exploited, this can lead to developing much more robust decisions and designing more resilient systems.

The barrier to aggressive use of emerging computational resources are thus less a matter of computational resources than of effective approaches for generating and interpreting large numbers of useful experiments, which is to say techniques for exploration. At present, very large compound computational experiments (simply stated questions that generate multiple model runs) are mostly based on exploring different parameter choices for a single model. While the value of parallel experiments with different plausible models is very clear, it is pragmatically more difficult, and innovation is needed to make such a practice routine.

Policy exploration with computer models is deeply related to uncertainty analysis. Understanding the potential implications of a candidate policy requires exploration across the range of possible outcomes of that policy. Our ability to assess policies requires that the range of model behaviors span the possible futures or states of the world consistent with our knowledge. Otherwise, exploration with computer models can produce biased conclusions. For example, while quantitative financial modeling routinely involves running large compound computational experiments (for example Monte Carlo simulations using probability distributions) failure to consider a wide enough range of future situations contributed to catastrophic failure of trading strategies based on these models in 2008.[1]

PARAMETRIC AND NON-PARAMETRIC EXPLORATION

Collections of alternative worlds, alternative futures, or alternative policy choices can with greatest generality be conceived as unordered sets or lists. However, tools for the exploration of such unordered collections are limited to random sampling, or exhaustive assessment if the set is small in size. If there is some structure relating the cases (a topology) so that nearby cases with similar properties to one of interest can be generated algorithmically, then a much wider range of tools can be employed to explore alternatives and draw inferences from the outcomes of modeling experiments. Typically, a single software program ('the model') is used that accepts a list of inputs (parameters). When these parameters are integer or real valued numbers there are a wide variety of mathematical techniques for choosing model cases for examination. Non-numeric parameters can also be related to one another, perhaps creating tree or lattice, in which case they also can be explored algorithmically.

Structuring the range of alternatives as a space with specified axes is a powerful analytic device even for non-quantitative and non-computational analyses. Our abilities to reason spatially can then provide a powerful means of drawing inferences from the patterns observed in the resulting space. The parameter or state spaces of most simulation models are very high dimensional, so that direct visualization of the complete space is not an option. But, lower dimensional summaries can be very informative, and can be produced for example by slicing (setting non-visualized dimensions to specific values), averaging, or using more complex operators to reduce dimensionality. From this perspective, point predictions or best estimate policy recommendations can be thought of as zero-dimensional data objects summarizing the larger dimensional space of possibilities. Modern computer resources allow us to create one, two, or three dimensional summaries that can be visualized graphically. The resulting pictures can provide more information, and better preserve user choice, than do single point 'answers'. In this way, many of the techniques of decision analysis can be understood as approaches to dimensionality reduction. And the art of policy analysis can be framed as discovering the most informative (and the least misleading) low-dimensional depiction of the underlying complexity.

A well established technique in the exploration of a single dimension of uncertainty is systematically testing a model parameter across a range of values ('ramping') while holding others constant. For example, in Axtell and Epstein (1999) issues of retirement timing were examined, and the number of rational actors in the population of agents was an uncertainty specifically addressed by ramping.

Beyond ramping over single variables, experimental designs over multiple variables can be used to better understand their interactions and to approximate the behavior of the model in question across the space they span (Kleijnen et al., 2005).[2] Full factorial designs can be used for small numbers of variables, but for problems with many dimensions of uncertainty and choice, require too many cases to be practical. A very useful alternative is the use of Latin-Hypercube designs (Cioppa and Lucas, 2007), which require many fewer cases, and can be space filling and unbiased.[3] (See Glossary.)

Search methods can also be used to explore spaces of alternatives, an approach that was used in operations research long before the advent of complexity science. In contrast with the problems addressed in classical operations research, the response surfaces of complex systems are typically rugged, and the identification of global optima is in general computationally intractable. Exploring the rugged landscapes of complex systems requires nonlinear optimization techniques, and the results of these computations in general provide only local information about the space being explored. Nonlinear optimization methods such as Genetic Algorithms (Goldberg and Holland, 1988; Holland, 1992; Mitchell, 1998), Tabu search (Glover, 1990), and simulated annealing (Kirkpatrick, 1984), must concern themselves with exploration as much as exploitation (Back and Schwefel, 1993). In contrast to search algorithms that seek single 'optimal' points in the input space of a model, for complex systems locating boundaries between qualitatively similar regions in a space of alternatives can often be much more useful (Horn et al., 1994; Bryan et al., 2006). For example, in the case of a company that has a standard hurdle-rate for internal rate of return of investments it considers, it can be very informative to determine the boundary between scenarios where a candidate investment achieves that return from scenarios where it will not. In addition to providing better information to decision makers, such 'level sets' can be very useful for Robust Policy Analysis (Bankes, 2002). In the case of an investment, knowing the situations where it would not perform adequately can help in constructing a more adaptive (hedged) option (McGrath and MacMillan, 1995). This is an example of mixed initiative planning, where computers and humans collaborate in finding good decision options. This is frequently more useful than having the computer present 'optimal' solutions as take it or leave it propositions.

EXPLORING POLICY SPACES

Decisions are fundamentally about choice, and computational examination of a wide range of possibilities brings with it the opportunity to discover options that would not have been considered without computational assistance. One manifestation of this is the use of computer models analogously to 'flight simulators'. By repeatedly playing with a simulation of the policy world, decision makers gain insight and experience, promoting better decisions when the real case presents itself.

A rather different approach is presented by the use of optimization as a means of formulating policy. Optimization can be a powerful method of selecting among options in engineering settings, but is often much less helpful for policy problems. An option that optimizes some value for an expected future, or the expected value over an assumed probability distribution of futures, will often be fragile when confronted with surprise. And for many policy settings, surprise is nearly inevitable. Hence, robust decision methods can often produce much better decision options than pure optimization approaches.

Further, in policy settings there is often not a single goal to be optimized. Rather, multiple values, measures, or objectives are important, and various stakeholders may have different priorities across these concerns. Similarly, different stakeholders frequently will have very different assessments of the probability of future circumstances. These concerns are sometimes addressed by forming a weighted average of stakeholder values and views, and then proceeding to solve for the best expected outcome in terms of the averaged value function. But this approach is unsatisfactory for multiple reasons. Notably, in a political context, stakeholders will routinely game their weightings of values and probabilities in response to their anticipation of the process used to reach a decision. The assumption of a unitary rational decision maker that is used in classical decision theory does not hold for many policy problems.

A broad exploration over the space of possible policies can produce a much more useful result than simple optimization for many problems. Information regarding how various options tradeoff among the metrics or values of interest can stimulate thinking, elicit new knowledge, and provide a backdrop to negotiations or other group processes. Clearly dominated options will often not be of interest. Focusing instead on policies where values are at tension (such as achieved levels of public service versus tax rates) results in a Pareto surface of non-dominated policies. A variety of Pareto search methods (for example multi-attribute genetic algorithms (Horn et al., 1994)) explore spaces of options in order to discover such tradeoff sets.

Providing policy makers with a trade space of feasible options can be much more desirable than computing a single recommendation for several reasons. Humans often are ill-disposed to yield decision making authority to a machine. This can reflect wisdom and not just parochial instincts. Often, policy makers will possess knowledge that was not used in any computation. This may be because they possess tacit knowledge that is difficult to formally express but that can enter as a 'seat of the pants' instinct in navigating a trade space. Some knowledge is more readily available after seeing an example. Only on seeing a bad option may one be able to verbalize what is wrong with it. Some knowledge cannot be made explicit for social or political reasons. Often tradeoffs among values are easier to make after inspecting alternative options than in an *a priori* elicitation. For example, directly specifying the monetary value of a human life may be unattractive, even though a tradeoff between lives and economic growth may be necessary. And most centrally, a trade space allows parties to a decision to trade horses and roll logs, constrained by the information in the computer, but not disempowered by it. Thus, computational analysis can constrain decisions, but not dictate them. This allows human and computational insight to be combined, in contrast to optimal recommendations that decisions makers must either accept or ignore.

In constructing trade spaces, it can often be useful to elicit values not as fixed utility functions, but as constraints. One might, for example, be willing to consider options with tax rates up to $X\%$, and this constraint may be a better representation of individual values than an explicit weighting of taxes versus public services. Humans in general satisfice rather than optimize (Simon, 1955, 1956, 1957). By eliciting the levels of outcome that would be satisfactory, constraints can be inferred that will generate the desired trade set. Defining the trade set through inequality constraints (satisfying threshold requirements on the various values) results in a level set in policy space. The goal of exploration then becomes estimating the boundaries of this level set, as discussed above.

An early example of this approach can be found in Brooks et al. (1999). This study sought to inform choices among possible future high-tech weapons by evaluating portfolios of weapon system stockpiles using a complex simulation model of an exemplary air campaign. For this problem, the optimal portfolio provides much less insight than does a level set on the response surface of the model in portfolio space. Shown in Figure 33.1 is such a level set of portfolios that result from setting a performance threshold 5% worse than the best performance that any portfolio can achieve. (Here the level set is projected onto the number of weapons of type 1 versus the number of weapons of type 2 plane.) This figure demonstrates several salient features. First, it immediately reveals a very strong complementarity between the two options shown on the axes, with critical stockage levels after which benefits are marginal. While readily explainable, this fact had not been noted before this figure was first produced. Further, the optimal portfolio was not near the center of the level set, but off on one wing. Consequently, the performance of the 'optimal' allocation will be much less robust to changes, errors, or missing information that modify the model's response surface. Experts presented with this diagram proceeded to 'explain' it, in the process producing information that had not been elicited prior to modeling. And as a result of these explanations, this diagram created much greater confidence that the model did not contain errors than resulted from the previous result of a single optimal allocation that had no accompanying explanation other than 'the model said so'. A diagram such as this one can provide a much better basis for negotiation between proponents of the two weapon systems than would be possible if only the optimal portfolio was provided. And should the decision maker have information or preference that was not available to the computer, that information can be used in making a choice from the trade space represented by the level set. If, for example, cost is an issue, the decision maker could opt for a choice near the bend, rather than a modestly more effective but much more expensive optimum. Similarly, information from multiple sources (competing models of the system in question perhaps) can be fused at decision time by determining the intersection of their respective trade sets.

EXPLORING UNCERTAINTY SPACES

If one had perfect knowledge about the world, then good policies could be reliably calculated by optimization. A model capturing this knowledge could be used to evaluate alternative policy options, and only issues of the computational complexity of the search process would merit discussion. With the exception of engineering simulations, this circumstance essentially never occurs. Available knowledge about policy problems is invariably partial and incomplete, and exogenous shocks and other surprises are always possibilities. Policy decisions must take into consideration issues of model uncertainty and risk, and confront the possibility that options that are optimal for the expected situation will be very fragile in the face of inevitable deviation from the expected.

It is thus a general requirement that policy analysis contend with the deep and unavoidable uncertainties that accompany policy problems. This need can be met by exploration of alternative assumptions, alternative models, and alternative futures.

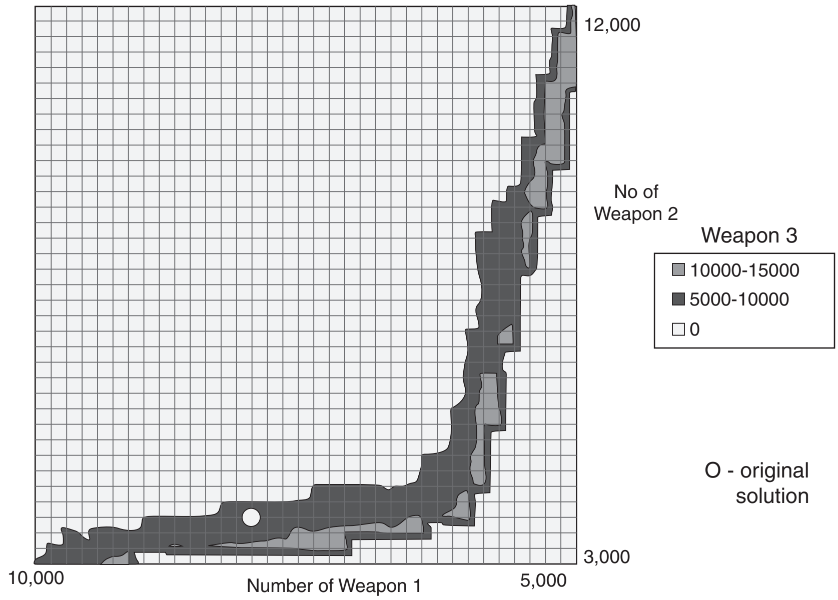

Figure 33.1 A level set in portfolio space

The variability of outcomes resulting from modeled uncertainties can be assessed by testing around an expected baseline case. However, such an assessment of stability is not sufficient for most decisions. The limitations of a computational policy analysis are better revealed by enumerating the most important assumptions required for a given choice, and discovering the possible failure modes for a candidate decision. In addition to alerting policy makers of the risks associated with a choice, it can also suggest alternative options that mitigate those risks.

Testing around an expected baseline case can be used to assess the variability of outcomes to modeled uncertainties providing an assay of stability. But the needs of decision making typically require other information. Discovery of possible failure modes of a candidate decision, and enumeration of the most important assumptions supporting a given choice are much more important devices for alerting policy makers of the limitations to a computational analysis, and can prompt consideration of other, possibly less risky, decision options.

Exploration over the uncertainties around a problem (in contrast to sensitivity analysis framed as analysis of variance) is akin to non-computational techniques such as scenario analysis (Schwartz, 1991; Millot et al., 1993) and assumption based planning (Dewar, 2002). Rather than try to predict the future, a dubious practice at best, these techniques try to understand the range of plausible, potentially important futures, and the assumptions that characterize them.

Non-computational techniques such as scenario planning have proven their worth in helping decision makers to escape the tyranny of the expected case, and to discover options that prepare for other possibilities. Their common weakness is that being purely human mediated, they are limited in the number of alternative assumptions or futures they can examine. Computer models of the policy problem together with tools for exploration can allow for the examination of massive numbers of scenarios, summarizing their implications for human users (Davis et al., 2007). Summarization can be accomplished through a combination of interactive visualization and statistical modeling of the results of exploration.

One method for statistical summary that has proven especially valuable employs statistical classifiers to summarize the assumptions that lead to qualitatively salient outcomes (Lempert et al., 2002, 2006). This has been called 'scenario discovery'. For example, a classifier analysis of the failure modes for a candidate strategy can give policy audiences an appreciation for the assumptions they will be making in adopting that option, and the possibilities that they would, in effect, be wagering against if they adopt it (Groves and Lempert, 2007; Groves et al., 2008; Lempert and Groves, 2010). Figure 33.2 displays two such failure scenarios discovered through this technique as part of an analysis of state water policy. In this case the classifier used to summarize the two regions where the candidate strategy underperforms was PRIM (Patient Rule Induction Method; Friedman and Fisher, 1999). This classifier captures regions of interest as rectangular boxes, which is a particularly convenient form to communicate the results to decision makers. Other classification methods can also be useful, in particular classification trees (Breiman et al., 1984).

Aggressive exploration across uncertainties can provide computational support for policy analysis in those situations where the uncertainties are so large that approaches involving prediction and probabilistic analysis founder. An extreme demonstration of this possibility is provided by Lempert et al. (2003) and Popper et al. (2005) where the outcomes from environmental policies across the uncertainties associated with a 100 year timeline were assessed by massive scenario analysis using a simple model.

Computational means for exploring uncertainties are much better developed for parametric uncertainty than they are for model uncertainty. When multiple models are available, testing candidate strategies against the suite of models can provide an assessment of

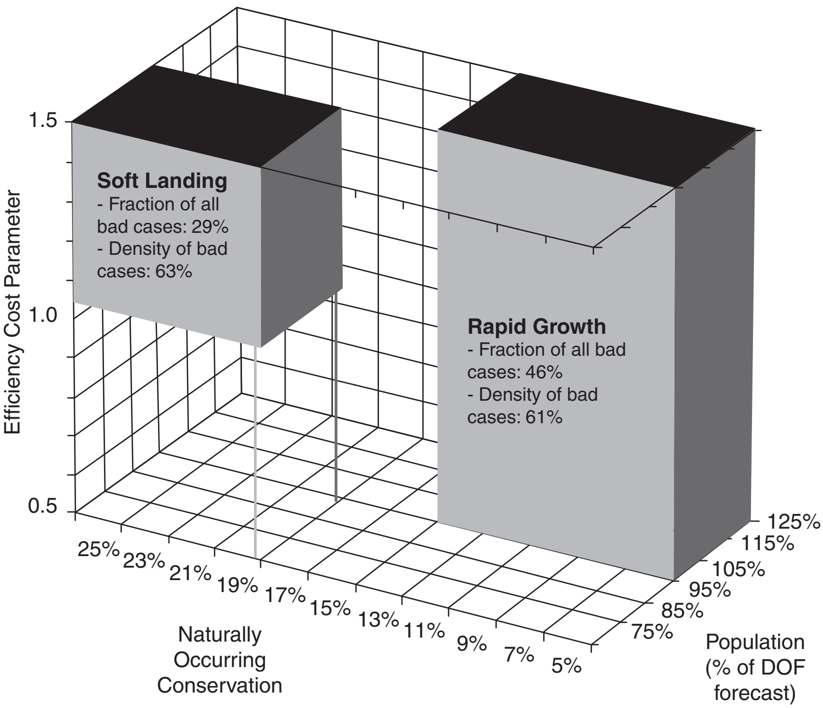

Figure 33.2 Two failure scenarios of a candidate strategy for resource management

possible model bias in favor of particular decision options. However, the current state of model building involves substantial labor in creating complex models encapsulating considerable data, theory, and assumption. In order for model uncertainty to be adequately addressed through computational exploration, tools are needed to algorithmically create complete models from components embodying single assumptions, theoretical snippets, or data sources. The recent successes of modeling infrastructures that support model composition[4] provide an indication of the feasibility of constructing models from pieces, and emergent software practices that support composition of software components (Szyperski, 2002) suggest that massive exploration across model variants is not infeasible.

JOINT POLICY-SCENARIO EXPLORATION: ROBUST DECISION METHODS

Exploration over scenarios and uncertainties can reveal the weaknesses of a given policy option, and exploration over policy can discover superior alternative policies. Combining them to jointly explore policies and uncertainties creates new possibilities for policy evaluation. In particular, joint exploration enables Robust Decision Methods (RDM) (Lempert, 2002; Bankes and Lempert, 2004; Bankes, 2005) that seek options highly immune to failure. Decisions optimized for the expected case (including for the expected probability distribution) can potentially fail disastrously in other, less expected, but possible circumstances. Frequently, joint exploration over decisions and uncertainties can reveal options that perform acceptably across a broad range of possibilities. These options will frequently be sub-optimal under all assumptions but sometimes can perform nearly optimally across a wide range of circumstances.

A variety of Robust Decision Methods result from different approaches to defining robustness, searching for robust options, and summarizing the results of that search. The oldest such approach is robust optimization, which as the name implies, optimizes a measure of robustness. Typically, robust optimization seeks the option that minimizes the maximum cost. This method can result in highly conservative solutions that can be very sub-optimal in likely cases to avoid high costs in low probability cases.

A different approach is to define a threshold performance past which a decision option is defined as failing, and then searching for policy options that minimize the occurrence of failure. An example of this is the info-gap approach (Ben-Haim, 2006) which specifies a linear nesting of sets of possibility and then defines robustness as the index of the greatest set for which an option performs acceptably. Methods of this type have a deep relationship to the literature in imprecise probabilities (Dempster, 1967; Shafer, 1976; Hand, 1993).

In general, sets of possible challenges are only partially ordered (they form a lattice), and so for more general methods, the result of search across sets of challenges for a fixed definition of robustness (i.e. a threshold value in some outcome) will be a set of robust candidates none of which are dominated by another. That is, different members of this set will fail on different scenarios. Unless information is available to unambiguously assign probabilities, no *a priori* information will be available to weight one failure scenario and hence one decision option over others. Thus, in general RDMs produce trade spaces where some additional information, assumption, or choice criterion must be provided to produce a final single strategy. Consequently, these general methods are not suitable for applications that require simple criteria producing unique solutions, but are well suited for applications where mixed initiative decision making is desired, with human users making choices from among machine provided trade sets. Figure 33.3 provides an example displaying the performance of alternative policies against two criteria (Lempert and Groves, 2010). It demonstrates both that adaptive strategies tend to

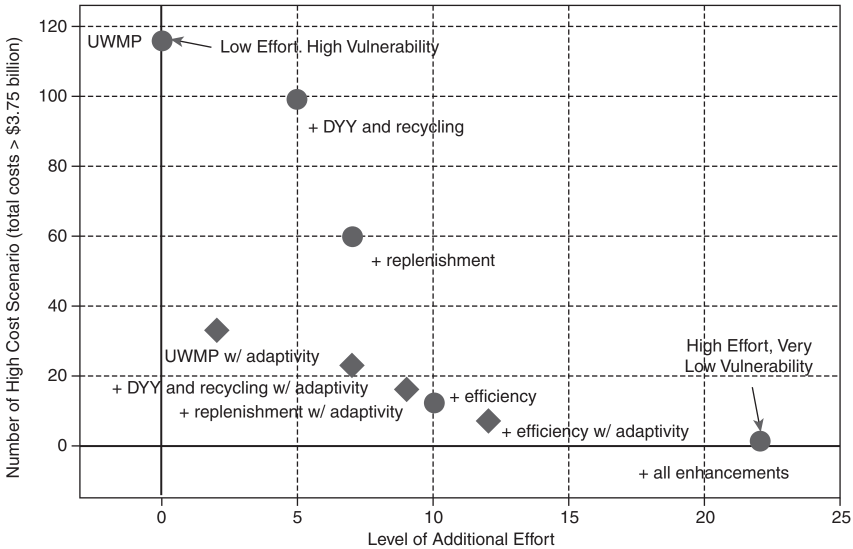

Figure 33.3 Tradeoffs between reducing vulnerabilities and effort for alternative state water policies. Circles indicate static strategies and diamonds indicate adaptive strategies. DYY refers to supply from MWD's dry-year-yield program

dominate (are more robust than) static strategies, and that different options may be favored depending on how policy makers tradeoff between criteria. Figure 33.4 more directly portrays the improvement in performance that can result from augmenting policies with adaptive mechanisms (Lempert and Groves, 2010).

Various algorithms can be used to search for robust strategies. Some approaches search over uncertainties to define a robustness measure, and then search over policies to maximize robustness. Bias inherent in the initial framing of the analysis can be addressed in part by iterating this process, searching for scenarios to defeat leading candidate policies, and then searching for options to cope with those scenarios. This technique can be used in particular to 'grow' adaptive policies from simple initial option sets (Lempert et al., 2003; Popper et al., 2005). Coevolutionary methods suggest themselves as potentially very useful in dual searches across challenge scenario and policy. Coevolutionary methods have been used to develop strategies for games or other closed problems (for example Pollack and Blair, 1998), and coevolutionary theory has seen great use in studies of environmental policy (Gowdy, 1994). However, there has been limited use of coevolutionary methods in policy exploration at this point, though it remains a promising idea.

EXPLORING OVER VALUES AND INFORMATION SOURCES

The use of exploration to discover sets of decision options that are robust to uncertainty can be extended to consider robustness to variation in other inputs to the decision. Particularly useful is exploration over values and information sources. Frequently, policy decisions are of concern to communities of 'stake holders', whose interests can be quite diverse. Contention between communities defending the environment and those promoting economic growth is a particularly common example of this. Also frequent are negotiations between representatives of different

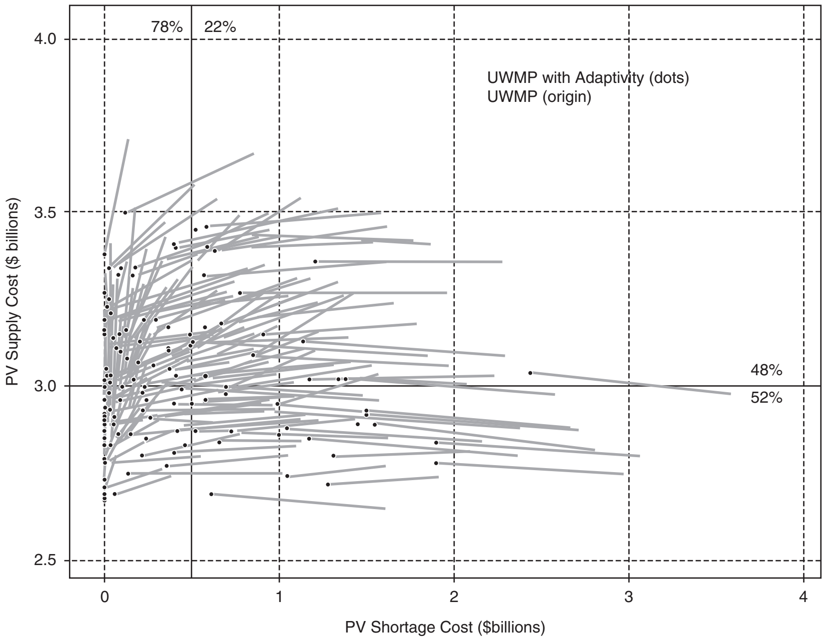

Figure 33.4 Differences in projected present value (PV) shortage costs ($ billions, x-axis) and supply costs ($billions, y-axis) for 200 scenarios for an Urban Water Management Plan (UWMP) strategy (unmarked line endpoints) with the same strategy that monitors signposts and adopts additional actions if the signpost is observed (marked line endpoints)

geographic areas, or different demographic populations.

Important decisions generally must balance a variety of interests. Individuals also have multiple interests, but with individual decision makers it is frequently possible to elicit weights for the various attributes of a decision, and then form a compound value function that is the weighted sum of its components. A policy can then be chosen to optimize this composite value function. This weighted sum approach does not work well with communities of stakeholders however. The process of eliciting weights quickly results in gaming and polarization among competing interests. And 'optimal' decision for some composite value function may be unsatisfactory for many or all of its constituents and they may have the ability to block a decision made on that basis. Robust decision methods provide an important alternative in these situations. Rather than form a fictitious composite interest function for optimization, solutions can be sought that are as robust as possible to the dissatisfaction of any interest group. In this context, choice sets that result from computational exploration can be a backdrop to community discussions and negotiation. The result is an ecosystem of decision making where the computational element can facilitate community discussions and consensus by imposing constraints on final decisions that emerge from accepted theory and available data, but that leave flexibility for negotiation where the implications of available information remain uncertain. Frequently in these contexts, knowledge emerges from human participants that they were initially unable to explicitly provide.

Communities with different values often also have different sources of information that they trust, or different models of the problem they believe in. In defense analyses for example, it is not infrequent that the Army's favored model and that of the Air Force provide somewhat different predictions and imply different decisions. In such situations, the models usually reflect the interests of their sponsors, even if there has been no conscious bias in their construction. Aggregating the recommendations that come from different knowledge sources, by for example simple averaging, is not a reliable method for reaching a good consensus. Robustness techniques can be used to determine policy options that are consistent with, to the extent possible, each of the contributing sources of information. As with multi-attribute decision problems, the result typically will be a trade set, and not a single uniquely defined option. In this context, implicitly held human judgments can be thought of as just another information source. Robust Decision Methods can thus be used as a means for knowledge fusion, including both machine and human resident knowledge.

This approach to the fusion of information sources can readily be understood from the perspective of constraint satisfaction. If each knowledge source is used to calculate a single 'optimal' decision, the recommendations of the various sources will in general differ. Instead each source can be used to derive a set of acceptable decisions (a level set resulting from a threshold of acceptable performance). In this alternative framing of the problem, resolution of the difference between knowledge sources, values, or expectations, is transformed into a relaxation of thresholds until the intersection of the solutions sets is non-null.

ITERATIVE AND INTERACTIVE EXPLORATION

Exploration of cases on a fixed model using a fixed analytic framework can reveal properties and hence implications of the knowledge contained in that model that otherwise would have remained hidden. However, the complex systems that concern policy decisions can seldom be reliably dealt with using a fixed model or framework that views the analyst and policy maker as outside the system. Instead, models and computation must often be understood as part of a socio-technical system where human and machine components each contribute to the discovery of solutions. In this context, a linear process of model creation followed by model exploitation, and of computation followed by interpretation is not adequate. Rather, a spiral process is needed where model creation, utilization, and interpretation are iteratively employed and multiple rounds of option selection and stress testing are supported.

Interactive exploration provides a means where the tacit knowledge of the analyst can be employed to guide machine search across high dimensional spaces of model cases or alternative models. This results in yet another sort of knowledge fusion, where knowledge implicit in the minds of users through interaction is combined with knowledge that is explicitly held within models.

Results from computational experiments provide insight to users and can stimulate reasoning. Human guidance steers search and iterative sampling to focus exploration on computational experiments more likely to be informative. Interaction between users and computers can by this means provide higher quality results than a linear approach where all human inputs are made at the beginning of a process of computational decision analysis, followed by a phase where computation occurs independently.

An example of the power of this approach is provided by Robalino and Lempert, 2000. This study used a method where a broad initial exploration of the space of inputs using a Latin Hypercube experimental design was used to support an analysis of variance. Based on this analysis, the eight inputs of greatest impact on the decision being investigated were then explored intensively. Conclusions reached on the basis of this analysis were then checked for counter-examples across the total input space. A genetic algorithm was used for this search, which resulted in four counter-examples. Each of these required extreme assumptions, and were dealt with in footnotes in the final paper.

Iteration and interaction provides an important means for coping with high dimensional spaces. Typical models will have large numbers of inputs, often numbering in the hundreds or thousands. The number of cases required to thoroughly explore the responses of even a simple model is often astronomical, and essentially infinite. This 'curse of dimensionality' has often been used in arguments against computational approaches, and as a defense for examining only a small number of cases, such as a base case plus variations. However, an iterative process that can, in principle, visit any part of the model's response space has properties possessed by no single static design. In such a process, the results of cases examined to a given point influence the choice of where to look next. Infinity is a mathematical concept that stands for no concrete object but can be defined through unbounded iteration. Similarly, iterative exploration, including human interaction, while not deductively closed, can inductively and abductively discover important properties of models with very high dimensional input spaces. The epistemological justification for conclusions drawn from explorations in highly dimensioned spaces is akin to that for experimental science generally. From a specific laboratory procedure that is in effect a sample out of an infinite set of experiments that might be conducted, general conclusions are often drawn. For example, after examining the response properties of a handful of neurons out of billions in a vertebrate brain, neuroscientists will advance theories about overall neural structure and function. Such theories advance science, and can win Nobel prizes, even though they may be overturned or significantly modified by subsequent experimentation. The single act of making an inference about billions of neurons from data about a handful may seem specious. But, embedded in the iterative process of normal science, where beliefs are tested and potentially falsified, our knowledge increases. Similarly, conclusions about the implications of a complex model based on a finite number of computational experiments drawn from a vast number that might be conducted can be very useful, even when there is no guarantee that all important behaviors have been observed.

LOOKING AHEAD – EXTREME MODELING TO SUPPORT RESILIENCY ANALYSIS

Complexity theory can make a major contribution to policy analysis in providing a basis for representing the interaction of multiple interacting systems and an accounting for the true uncertainty attending our knowledge about causal relationships. However, the incorporation of complexity concepts in models that are then used in a reductionist fashion may do little to improve upon previous approaches to scientific policy analysis. An agent-based model can embed just as many questionable assumptions as a linear calculation with matrix algebra. Consequently, developing models that incorporate complexity concepts but then using them for prediction and forecasting simply adds nonlinear modeling representations to fundamentally reductionist practice (Richardson, 2003). In order to fully bring the insights of complexity science to policy, they must be applied not only to the construction of models but to their use. Institutions and decision makers are part of the systems they manage. In order to incorporate a complexity standpoint into policy formulation, the complete socio-technical system must be considered, including models of the system, the policy makers, and their decision processes.

A reductionist decision process using complexity models will not suffice to create systems adequate to deal with deep complexity. Novel modeling methodology and technology is needed that will allow problem framing, modeling, and decision to be agilely combined within an entrepreneurial process (MacMillan and Boisot, 2004). Linear analytic strategies will not suffice to deal with the challenges of complex systems nor will they allow computational science to achieve its full potential.

Ivory tower modeling methods that study systems from afar can be fruitful for academic theory development. But, in order to cope with highly complex and deeply uncertain systems it is going to be necessary to build models as they are to be used. Frequently, the system under study may change between model development and exploitation. Consequently, for complex problems, what is needed is not a single fixed and validated model but 'just in time' support for modeling. For modeling to have a useful role as a component of a complex system, new modeling techniques and methods are needed. These may perhaps be thought of as 'extreme modeling', analogous to extreme programming. Modeling techniques akin to programming innovations devised to support Web 2.0 applications (O'Reilly, 2005) are needed that can provide the agility needed to contend with volatile environments, emergent requirements, and continuous model development.

At present, static closed models are used to represent open and evolving systems. Methods for creating open and adaptive model based infrastructure are needed to better suit these problems. Such open representations will presumably consist of a small, highly conserved kernel, and a much larger and more rapidly adapting periphery, just as do existing open source software projects and crowd sourcing based web applications (Kazman and Chen, 2009). Depending on the application, rates of change in the periphery will vary as well, resulting in the pace layering seen in many engineered and natural systems (Brand, 1999; Gunderson and Holling, 2002).

In this way, the process of modeling complex systems must evolve to more closely resemble the systems with which it contends. Just as the phenomena of interest are pace layered and emergent, so modeling itself must produce models composed from components that adapt to changes in their environment with varying paces of change. The challenges of doing this are significant. But the opportunity is for complexity modeling to become ubiquitous. Rather than a specialized activity that sits outside most of human life and economic activity, computational modeling can become a major means by which humans communicate with their technology. The practice of extreme modeling, which at this moment exists only in prospect, will allow us to cross the chasm between model creation and model use which has consigned computational science to a peripheral role up to now. The role of the computational scientist in this vision would not be the creation of final models but rather the creation of modeling infrastructure. That infrastructure would capture knowledge but also provide means of adaptation. Many capabilities may prove useful in establishing this approach, including improved means of representing and reasoning with structural model uncertainty, the ability to create models from composeable parts, and mixed initiative modeling where model snippets, human judgment, and data can all be used in the creation of model instances.

One of the great challenges before our technological culture is creating systems and institutions that are highly resilient in the face of complexity and deep uncertainty. Resiliency involves both robustness to external shocks and adaptive mechanisms that allow for recovery even when robustness fails. To play its role, complexity modeling must be able to adapt to changes both frequent and rare, and be able to contend with future situations that cannot now be anticipated. In reaching that goal, complexity modeling can play a key role in making society resilient to future surprises.

NOTES

1 In particular, financial modelers assumed Normal probability distributions underestimating the probability of extreme events, and in many cases allowed the absence of knowledge about correlation among sources of risks or the behavior of other traders in the market to be modeled as an assumption of no correlation. Testing a wider range of assumptions would have revealed the risks that this era of financial modeling concealed.

2 This approach is sometimes associated with the phrase 'Data Farming' (Brandstein and Horne, 1998).

3 Latin Hypercubes (LH) are statistical designs for experiments that are very useful in assessing the behavior of a model in a high dimensional space of cases through a limited number of computational experiments. In contrast to full factorial designs, where the number of cases needed grows exponentially with the dimensionality, LH allows the specification of the number of experiments that can be afforded, and creates a design of experiments that still provides a statistical cover for the space. In contrast with Monte Carlo sampling approaches, LH is space filling, and does a better job at sampling from the corners and edges of the multi-dimensional cube of cases, where extreme or unusual model behavior may often be discovered. (See further description in the Glossary.)

4 Examples include COMPOEX (Waltz, 2008) and the Computer Assisted Reasoning system – CARs (Bankes et al., 2002).

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34

Complexity, Habits and Evolution

Geoffrey M. Hodgson

INTRODUCTION

This chapter addresses what are often described as 'complex adaptive systems'. Typically such systems involve populations of entities that store and replicate information. But these micro aspects are less fully explored in most accounts, which concentrate on macro-outcomes of complex adaptive systems, particularly self-organization and emergent properties. These omissions are addressed here, with a stress on the roles of individual habits and organizational routines. It is argued that such considerations open up the possibility of a meta-theoretical evolutionary framework for understanding complex adaptive systems. This essay also makes use of some insights from evolutionary and institutional economics and contrasts its approach with some standard assumptions in mainstream economics.

The growing appreciation of the complexity of social as well as natural phenomena has promoted a diversity of responses, especially within the social sciences, including varieties of relativism, post-modernism and post-structuralism (Morçöl, 2001). Important ideas within the complexity narrative include self-organization, autopoiesis, emergent properties, requisite variety, non-linearity, path dependence, positive feedback, chaotic behaviour, and so on. But while these are important concepts, neither singly nor jointly do they amount to a unifying theory of complex phenomena.

Is such a theory possible? Paul Cilliers (1998: ix) claims that complexity itself rules out such an over-arching theory. Notably his argument would apply to natural as well as social phenomena. Yet despite the complexity of the natural world, scientists have made considerable progress in developing explanatory frameworks and theories, even if the task of prediction is often confounded by complexity. To take an example, while the human body is highly intricate, successful curative medicine is possible.

Stephen Wolfram (2002) argues that complex phenomena can be generated by simple, algorithmic rules. While the outcomes are often unpredictable because of nonlinearities, their understanding and explanation centres on the generative algorithms or programs. A danger here is the conflation of reality with a computer simulation. Simple algorithms can give rise to complex outcomes but that does not mean that the complexity we find in reality has an equivalent and equally simple origin.

The apparent absence of a unifying theoretical framework has encouraged the sceptics. One of these is John Horgan (1995) who critiqued the original claims of some complexity theorists (including those at the Santa Fe Institute) that they were in sight of a grand unifying theory of complex phenomena.

I agree with Horgan that such a grand unifying theory is very far from our grasp. Its elevation to a major objective is a symptom of a tendency to excessive generalization that has caused serious problems, at least in the social sciences. Among these is the neglect of historical and other specific phenomena and their specific roles and dynamics. Much of post-war economics and sociology has been diverted into a competitive quest for ever-greater generality and abstractness, to the reckless neglect of specific phenomena (Hodgson, 2001). Despite the generation of a number of important insights, it is increasingly acknowledged that there is no unified and coherent narrative worthy of the title of 'complexity theory' (Anderson, 1999; Marion, 1999).

But both advocates and critics of 'complexity theory' have been diverted by universalities. The advocates have hunted for general principles that might apply to slime moulds, piles of sand, tree leaves, chemical reactions, astronomical bodies, weather systems and much else, including all human organizations and societies. Their very limited success is the cue for the critics, some of whom bemoan the failure to come up with anything remotely like Newton's laws or the general theory of relativity.

Any theorization of complexity applied to human societies or organizations, addresses a specific set of phenomena. We consider some of the very basic features of this set and establish that they apply to a large class of natural phenomena as well. Furthermore, it is then possible to establish some general principles that apply to this broader domain. But the nature of these principles is very different from the aforementioned 'laws' that have been established in physics.

I am concerned with complexity in human society. Consequently, I start the argument with the human agent, placed in a social and natural context, interacting with others. The ontological and epistemic complexity of this configuration is acknowledged. I then point to some basic cognitive and behavioural mechanisms that are necessary to deal with this complexity. There are some related but very different mechanisms in the natural world. There are also related mechanisms at the higher level of social organization. These communalities at three different levels point to some limited over-arching principles relevant to all complex systems in this broad class. But before I outline the nature of these principles it is necessary to dispense with some rival claims, such as the universality and sufficiency of self-organization theory. Once this is done I make a specific claim concerning the evolutionary character of most complex adaptive systems. This claim is well over a hundred years old, but it is relatively neglected, and some theorists may find it surprising.

ADAPTIVE POPULATIONS

Much of the work carried out under the rubric of complexity research makes quite specific ontological assumptions. Much of 'complexity theory' addresses not complex phenomena in general, but a particular form of complexity typically described by John Holland (1992), Brian Goodwin (1994), Stuart Kauffman (1995), Ralph Stacey (1996, 2003) and many others as a 'complex adaptive system'. In practice, such systems are made up of multiple interconnected entities. In complex adaptive systems theory a number of agents interact with each other and together form a system that adapts to its environment. Also the individual entities are adaptive in that they have the capacity to change or learn from interaction and experience. A central question is: how do such complex nonlinear systems function to produce ordered and novel patterns of behaviour, in the absence of any overall blueprint or ruling designer? We are dealing not merely with singular wholes, but with populations of adaptive agents that interact with others and form structured relations, which themselves adapt through time.

Consider the basic nature and capacities of these agents. In real circumstances they need inputs of matter or energy to survive. They face a complex and changing social and natural environment, posing vital problems that require solutions. They cannot only replicate and pass on some of their capacities and physical characteristics, but also they can communicate useful knowledge and techniques. This broad description applies to human society and to a large number of types of natural and artificial phenomena: but it is not universal. By sacrificing its universalist objective and specifying a particular ontology, complexity theory can make significant further progress.

The predominant emphasis in the literature on complexity has been on the structure and adaptations of the system as a whole and not on the individual components. The explanatory focus has been on the possible emergence without design of organization and orderly patterns of behaviour. This agenda is important and valuable. But it is one-sided. The emphasis has been on the complexity of the system, rather than on the complexity of the components, their environments, and the adaptive problems that they face. Discourses on self-organization, spontaneous order and autopoiesis acknowledge the interacting components, but often – perhaps in the pursuit of universal explanations – fail to consider adequately their particular characteristics and micro-contexts.

I propose to bend the stick in the other direction. I shall concentrate first on the interacting agents and their complex environments. Macro-systemic considerations will be brought in later.

The next section briefly reviews the treatment of agents and their environments in mainstream economics. After revealing various limitations, we consider contrasting approaches in dealing with complexity in the section after that.

HYPER-RATIONALITY IN MAINSTREAM ECONOMICS

Although mainstream economists urge us to take individuals and their incentives seriously, in their pursuit of the 'science of choice' they have overlooked the complexity of the decision environment, and the limitations of human cognitive and communicative capacities when faced with this complexity. They have assumed that individuals can perform immense feats of deliberation and calculation, or that it is legitimate to assume that individuals act 'as if' they had such capacities. It is only since the 1990s that these assumptions have been successfully contested on mainstream terrain, despite the longstanding complaints of several heterodox critics including Thorstein Veblen (1898) and the Nobel Laureate Herbert Simon (1957).

Even today, with significant mainstream acknowledgement of 'bounded rationality', contrary ideas remain entrenched in some quarters. The rational expectations hypothesis is still widely used in economic models: it assumes that outcomes do not differ systematically from what people expected them to be, and that people have the mental capacity to process all available information. Significantly, some influential challenges to this hypothesis have used insights from chaos theory. Non-linearities make predictions by agents difficult or impossible (Akerlof and Yellen, 1985; Grandmont, 1987). The rational expectations hypothesis is also challenged by models where a small minority of agents are not fully rational. Outcomes can diverge radically from models where agents all have equivalent rational capacities (Haltiwanger and Waldman, 1985).

Despite all its emphasis on the individual, mainstream economics often assumes that individual preferences are similarly structured or identical, and that information-processing capacities are equivalent. Relaxation of these assumptions often leads to a breakdown of mainstream results (Arrow, 1986).

Furthermore, although economists have relaxed the 'perfect information' assumptions of earlier decades, to embrace various forms of incomplete or imperfect information, cognitive divergences are rarely acknowledged. The 'Harsanyi doctrine' is still commonplace: this attributes differences in individuals' beliefs entirely to differences in information and upholds that every individual interprets information in the same way. Yet in reality cognitive divergences are typical. That is one reason why conversation and communication are important. They help (albeit with limited success) to overcome different interpretations and establish some common meanings. Cognitive divergence is an important facet of the complexity that we all face in social interactions, yet the Harsanyi doctrine assumes it away.

Game theory is at the cutting edge of mainstream economics. One form of game theory assumes not only that agents are rational, but also they know and fully take into account the rationality of others: this is the 'common knowledge of rationality' assumption. But some game theorists have moved away from this supposition of hyper-rational agents, with theoretical results that are strikingly different from those where common knowledge of rationality is assumed (Gintis, 2000; Camerer, 2003).

Overall, mainstream economics has only partially moved away from assumptions of agent rationality and homogeneity. Where such moves have been made, they have led to very different results. Mainstream economics has half-opened the Pandora's Box of complexity but does not know how to keep its contents under control.

THE NATURE OF HABIT

Contrasting assumptions are found in non-mainstream thought, including within evolutionary and institutional economics. By contrast, these approaches start from the assumptions of heterogeneous agents, cognitive divergence, and complex interaction. Known forms of mathematical analysis meet barriers of intractability in such circumstances, and consequently one has to fall back on indicative theorizing including agent-based computer models, case studies and historical research.

Rather than starting *a priori* from relatively simple models of rational individuals and trying to draw logical conclusions from their assumptions, these approaches rely much more heavily on psychological and cognitive research to understand how boundedly rational agents deal with uncertainty and complexity. The work of William James (1890) is highly relevant here. He founded a school in psychology that stresses the role of habits in dealing with complexity and uncertainty. His work inspired evolutionary and institutional economists such as Veblen (1898, 1914), philosophers such as John Dewey (1922) and is enjoying a renaissance today (Johnson and Henley, 1990; Plotkin, 1994).

Instincts are inherited biologically. By contrast, habits are conditional propensities moulded by environmental circumstances and transmitted culturally rather than biologically. The mechanisms of habit are largely unconscious, but they may press on our awareness. Habits are submerged repertoires of potential behaviour; they can be triggered or reinforced by an appropriate stimulus or context. The meaning of habit adopted by James (1890), Veblen (1898) and Dewey (1922) was of an acquired proclivity or capacity, which may or may not be actually expressed in current behaviour. A similar interpretation of habit as a disposition is found in the work of contemporary psychologists (Ouellette and Wood, 1998; Wood et al., 2002; Wood and Neal, 2007).

Brain imaging studies on human subjects (Poldrack et al., 2001) show that the formation of habits involves a shift away from parts of the brain associated with conscious, declarative memory and goal-setting (the medial temporal lobe and pre-frontal cortex) towards areas associated with procedural memory and context-triggered responses (the basal ganglia).

This conception of habit contrasts with that used by some other authors. For example, the Nobel economist Gary Becker (1992: 328) wrote: 'I define *habitual* behavior as displaying a positive relation between past and current consumption'. Becker here defines habit not as a behavioural propensity but as sequentially correlated behaviour. In contrast, the view of habit here is of a disposition, which, once acquired, is not necessarily realized in any future behaviour. Habit is a causal mechanism, not a set of correlated events. Repeated behaviour is important in establishing a habit. But if we acquire a habit we do not necessarily use it all the time.

HABITS AND COMPLEX ENVIRONMENTS

In terms of energy requirements, the brain is very expensive. While it accounts for less than 2% of our weight, it consumes up to 20% of our calorific intake (Drubach, 2000). Bigger brains mean that we have to consume more calories, and our ancestors had to spend more time on hunting and gathering. The evolution of the human brain was a trade-off between its survival advantages and its energy costs.

Rather than trying to amass and process all information, habit is a much cruder way of storing information from past experience. It vastly economizes on brain storage capacity. Habit crudely encapsulates past adaptive behaviour: much information is not retained. The capacity to form habits has evolved in humans to cope with complex changing environments with large amounts of information, given the limited capacity and energy costs of the human brain.

The role of habit is illustrated by an agent-based computer simulation developed by Thorbjørn Knudsen and myself (Hodgson and Knudsen, 2004a). The simulation considers the evolution of a traffic convention, concerning whether to drive on the left or right side of a circular track. Agents make decisions through weighted combinations of 'rational deliberation' on current information and habitual dispositions to drive on one side rather than the other. The most important result of these simulations concerns the effect of introducing habit into the modelling of agent behaviour. In most of parameter space, strength of habit can increase the systemic rate of convergence towards a left/right convention. In some circumstances it can also enhance systemic resistance to error. In short, habit helps agents to deal with uncertainty, complexity and change. It requires less mental storage capacity than fully rational deliberation.

Another computer simulation that illustrates the role of habits (or similar rule-like behavioural dispositions) in complex environments was performed by Giovanni Dosi et al. (1999). Their work addresses the computability and complexity of the decision procedures of agents. Instead of taking an axiomatic approach grounded on the principles of rationality and optimization, they use algorithms where decisions are evolving outcomes of processes of learning and adaptation to the particular environment in which the decision must be made. They apply genetic programming (Koza, 1992) to agent behaviour in oligopolistic markets. Consistent with evidence of the behaviour of real economic agents, the simulation shows that the response to complexity is often to increase the reliance on behaviour driven by relatively simple rules.

Both simulations establish that the higher the ratio between the complexity of the environment, on the one hand, and the informational and deliberative capacities of agents, on the other, the more that agents have to rely on something like habit, and the more efficacious it becomes in the circumstances. Habit is a vital psychological mechanism to deal with complexity and change.

Often acquired through cultural transmission, habits serve as means of learning skills and fixing useful knowledge in human societies. Anthropologists Peter Richerson and Robert Boyd (2001) have argued that human capacities to develop and transmit a sophisticated culture evolved during periods of rapid climate change, when the relatively rapid transmission of useful knowledge on how to adapt to the environment was vital. Biologically inherited instincts have important uses, but they change far too slowly to accommodate new knowledge in complex and changing environments.

Without habits our brains cannot deal with the vast amounts of information involved. For example, when using a language, we cannot deliberate upon every element. Such calculations would bring discourse to a halt. We have to rely on acquired habits to deal with standard linguistic rules, so that the brain is freed up to contemplate higher-level decisions. Similar remarks apply to all human skills of thought or behaviour. In a complex world, habit is a necessary foundation for our knowledge and skills.

FROM HABITS TO ORGANIZATIONAL ROUTINES

In everyday parlance the word 'routine' is used loosely to refer to repeated sequences of behaviour, by individuals as well as by organizations. But when Richard Nelson and Sidney Winter (1982) used the concept in their seminal work on economic and organizational evolution, and repeated the metaphor of 'routines as genes', they suggested a more specific and technical meaning for the term. It is important to clarify and refine this technical meaning.

A consensus has now emerged that routines relate to groups or organizations, whereas habits relate to individuals (Cohen et al., 1996; Dosi et al., 2000). Individuals have habits; groups have routines. But routines do not simply refer to habits that are shared by many individuals in an organization or group. Routines are not themselves habits: they are organizational meta-habits, existing on a substrate of habituated individuals in a social structure. Routines are one ontological layer above habits themselves.

Nelson and Winter (1982) refer repeatedly to 'routines as genes'. This is another useful analogy. But of course, as these authors emphasize, routines are very different from genes. Routines do not replicate biologically and they are much less enduring. All analogies are inexact in some respects and must be handled with care. The gene analogy usefully points to routines as relatively durable carriers of information through shorter periods of time, with the capacity to generate particular outcomes in given circumstances. Routines are like genes in the abstract sense that they are both generative, rule-like structures and potentialities.

Contrary to some ambivalence in the literature, routines (like habits) are best treated as stored behavioural capacities or capabilities rather than behaviour as such (Hodgson, 2008). Consider a firm in which all employees and managers work between 9 am and 5 pm only. During this working day a number of organizational routines can be energized. At other times the firm is inactive. But the routines do not all disappear at 5 pm, to reappear mysteriously the next day. The routines-as-capacities remain, as long as the individuals have the potential and disposition to work again together in the same context. Subject to this condition, the routines can be triggered the next day by appropriate stimuli.

Routines energize a series of conditional, interlocking, sequential behaviours among individuals within the organization (Cohen and Bacdayan, 1994). Routines depend upon a structured group of individuals, each with particular habits, where many of these depend upon procedural memory. The behavioural cues by some members of a structured assembly of habituated individuals triggers specific habits in others. Hence various individual habits sustain each other in an interlocking structure of reciprocating individual behaviours. Together these behaviours take on collective qualities associated with teams. The organization or group provides a structured social and physical environment for each individual, including rules and norms of behaviour, of both the explicit and the informal kind. This environment is made up of the other individuals, the relations between them and the technological and physical artefacts that they may use in their interactions. This social and physical environment enables, stimulates and channels individual activities, which in turn can help trigger the behaviour of others, produce or modify some artefacts, and help to change or replicate parts of this social and physical environment.

Hence organizations have important additional properties and capacities that are not possessed by individuals, taken severally. The organization provides the social and physical environment that is necessary to enable specific activities, cue individual habits and deploy individual memories. If one person leaves the organization and is replaced by another, then the new recruit may have to learn the habits that are required to maintain specific routines. Just as the human body has a life in addition to its constituent cells, the organization thus has a life in addition to its members. The additional properties of the whole stem from the structured relations and causal interactions between the individuals involved (Blitz, 1992; Weissman, 2000; Hodgson, 2004).

The above discussion has established that, in addition to genes at the biological level, there are additional information-carrying mechanisms in human societies, namely habits at the individual level and routines at the organizational level. An abstract communality exists, despite huge differences at the level of detail. The significance of this point will be developed later. But we are already hinting at the possibility of extending the use of Darwinian principles beyond the biological sphere.

SELF-ORGANIZATION *VERSUS* DARWINISM?

Emergent properties are a facet of 'self-organization'. Organizations have undesigned properties that are not features of individuals, taken severally. Let us tackle the relationship between self-organization and Darwinism, before elaborating the relevance of the latter and returning to the role of habits and routines.

Much has been written on how our knowledge of complexity should modify the Darwinian theory of evolution, particularly through the acknowledgement of the role of self-organization (Depew and Weber, 1995). Some interpreters of this work go so far as to suggest that self-organization provides an alternative to Darwinian theory. These interpretations are mistaken, both in terms of their misunderstanding of the claims of leading theorists of self-organization, and in the viability of their claim.

Self-organization may be necessary to explain the emergence of a number of complex phenomena. But in the absence of selection there is little chance of the development of increasingly complex structures. Thus, rather than being alternatives, Kauffman (1993: 465) saw a 'natural marriage of self-organization and selection'. He and several other pioneers of self-organization theory do not present their argument as an alternative to Darwinian theory. Jeffrey Wicken (1987) wrote of 'extending the Darwinian paradigm', not exterminating it. David Depew and Bruce Weber (1995) considered 'Darwinism evolving', not Darwinism abandoned. Weber and Depew (1996: 51) wrote:

> the very concept of natural selection should be reconceived in terms that bring out its dynamical

> relationships with chance and self-organization. In our view, Kauffman's recent work, as expressed in *The Origins of Order*, does just this.

What is involved here is a revision and extension of natural selection theory, not its negation. Kauffman (1995: 8) himself called for a 'revision of the Darwinian worldview' not its abandonment. As Kauffman (1993: 644) also related:

> I have tried to take steps toward characterizing the interaction of selection and self-organization. … Evolution is not just 'chance caught on the wing'. It is not just a tinkering of the ad hoc, of bricolage, of contraption. It is emergent order honored and honed by selection.

Once self-organized systems and subsystems emerge, natural selection acts upon these self-organized structures once they emerge. Far from being an alternative to natural selection, self-organization requires it in order to determine which self-organized units have survival value. Accordingly, other self-organization theorists, such as the biologists Scott Camazine and his colleagues, similarly recognize that self-organization complements rather than displaces the 'orthodoxy' of natural selection. Echoing Kauffman, Camazine et al. (2001: 89) write,

> There is no contradiction or competition between self-organization and natural selection. Instead, it is a *cooperative 'marriage'* in which self-organization allows tremendous economy in the amount of information that natural selection needs to encode in the genome. In this way, the study of self-organization in biological systems promotes orthodox evolutionary explanation, not heresy.

Consequently, evolutionary economists who propose that self-organization theory is an alternative to Darwinian principles are at variance with their prominent mentors in self-organization theory. Leading theorists of self-organization recognize that natural selection is required at some point in the explanation.

Crucially, an exclusive focus on self-organization concentrates on the development of the entity, neglecting its interactions with its environment and providing no adequate explanation of how the entity comes to be adapted to survive in this environment (Cziko, 1995). The mistake is to concentrate entirely on internal development and evolution from within, even to the extent of defining evolution in these narrow and unwarranted terms.

On the contrary, in biology, neither individuals, species, nor ecosystems are entirely 'self-transforming'. Evolution takes place within *open* systems involving *both* endogenous and exogenously stimulated change. Generally, evolution takes place both through internal changes and interactions with the (possibly changing) environment.

THE DARWINIAN EVOLUTION OF COMPLEX ADAPTIVE SYSTEMS

Darwin himself (1859: 422–423; 1871, vol. 1, 59–61, 106) hinted at the possibility that his core principles might apply to other evolving systems, such as human language. This insight was taken up by others in the nineteenth century (Ritchie, 1896; Veblen, 1899), revived later in the twentieth century (Campbell, 1965), but is only recently receiving wider attention.

Theorists working in this area suggest that in typical 'complex adaptive systems' Darwinian core principles are not only relevant but *ultimately unavoidable*. Importantly, there is no adequate rival over-arching theory to deal with these systems.

Most 'complex adaptive systems' involve populations of adaptive agents that interact with others and form structured relations, which themselves adapt through time. To emphasize their population properties, they are described elsewhere as 'complex population systems' (Hodgson and Knudsen, 2006; Aldrich et al., 2008).

By definition, entities in complex population systems face specific problems that have to be solved to minimize degradation and raise the chances of survival. In short, these entities are engaged in a *struggle for existence*, to use the term adopted by Darwin (1859: 62–63).

We also assume some capacity to retain and pass on to others workable solutions to problems faced in the struggle for existence. Examples include tools and technological know-how. Retaining such problem solutions or adaptations means avoiding the risks and labour of learning them anew. Given that the entities in the population are mortal and degradable, there are also good reasons to assume that some capacity exists to pass on to others information about such workable solutions. This is the basis of the Darwinian *principle of inheritance*.

In sum, a complex population system involves populations of non-identical (intentional or non-intentional) entities that face locally scarce resources and problems of survival. Some adaptive solutions to such problems are retained through time and may be passed to other entities. Examples of such complex population systems are plentiful both in nature and in human society. They include the ensembles of every biological species, from amoebas to humans. In addition, they include collections of human organizations such as business firms, as long as these organizations are cohesive entities with a capacity to retain and replicate problem solutions.

Crucially, an adequate explanation of the evolution of such a system *must* involve the three Darwinian principles of variation, inheritance and selection. These are the broad Darwinian theoretical requirements. They do not themselves provide all the necessary details, but nevertheless they must be honoured. Otherwise the explanation of evolution will be inadequate.

Consider the three Darwinian principles in turn. Each principle is an explanatory requirement. First, there must be some explanation of how variety is generated and replenished in a population. In biological systems the answers – established since Darwin's death – involve genetic recombination and mutations. By contrast, the evolution of social institutions involves innovation, imitation, planning and other mechanisms very different from the detailed processes found in biology (Aldrich and Ruef, 2006). The general problem of the existence and replenishment of variety remains a vital question of evolutionary research in the social and technological domain (Nelson, 1991; Saviotti, 1996; Metcalfe, 1998). Innovations are a common source of new variation, but the determinants of such novelties are not fully understood.

Second, there must be an explanation of how useful information concerning solutions to particular adaptive problems is retained and passed on. This requirement follows directly from the broad nature of the complex population system that we are required to explain, in which there must be some mechanism by which adaptive solutions are copied or passed on. In biology these mechanisms often involve genes and DNA. In social evolution we may include the replication of habits, customs, rules and routines, all of which may carry solutions to adaptive problems (Veblen, 1899; Nelson and Winter, 1982; Hayek, 1988). There must be some mechanism that ensures that some such solutions (embodied in habits, routines or whatever) endure and replicate; otherwise the continuing retention of useful knowledge would be impossible.

Third, and not least, there must be an explanation of the fact that entities differ in their longevity and fecundity. In given contexts, some entities are more adapted than others, some survive longer than others, and some are more successful in producing offspring or copies of themselves. Here the *principle of selection* comes in. Selection involves an anterior set of entities, each interacting with its environment and somehow being transformed into a posterior set where all members of the posterior set are sufficiently similar to some members of the anterior set, and where the resulting frequencies of posterior entities depend upon their properties in the environmental context (Price, 1995; Andersen, 2004; Knudsen, 2004). Through selection, a set of entities, a population, will gradually adapt in response to the criteria defined by an environmental factor. Thus in a cold environment, the proportion of mammals with more fat or long fur is likely to increase.

The principle of selection is different from the principle of variation. The latter is the requirement for some explanation of the sources and replenishments of variety. Selection refers to the mechanisms that bring about the survival of some variations rather than others, often reducing variety. Even when both variety-creation and selection involve human agency, as often is the case in the human domain, the two processes are quite different. Innovation is about the creation of new variations; selection is about how they are tested in the real world.

Note that outcomes of a selection process are necessarily neither moral nor just. Furthermore, there is no requirement that outcomes of a selection process are necessarily optimal or improvements on their precursors. Insofar as these outcomes carry connotations of refinement or efficiency, it is efficiency relative to the given environment, and efficiency that is tolerable rather than optimal. Darwinism does not assume that selection brings about globally efficient or (near) optimal outcomes, and in certain instances selection can even lead to systematic errors (Hodgson, 1993). There is no reason to believe that the special requirements needed to asymptote global efficiency are generally prevalent in nature or society (Winter, 1964; Gould, 2002).

Without honouring the principle of selection, we have no way of explaining how some entities or their offspring prevail over others. The principle is widely held to apply in the natural world; the fitter members of the species often have greater chances of survival and procreation. This helps to explain how species become adapted to their environment. But the move from the natural to the social world does not undermine the principle of selection. Even if there is not a fierce life-and-death struggle between rival customs or institutions, some explanation is required of why some enjoy greater longevity than others, why some are imitated more than others, and why some diminish and decline. Any such explanation must come under the general rubric of selection, as defined above.

Darwin's principles of variation, inheritance and selection are required not only to explain evolution within populations but also the origins of those populations themselves. Overall, as long as there is a population with imperfect inheritance of their characteristics, not all of them having the same potential to survive, then Darwinian evolution will occur.

CONCLUSION: HABITS, ROUTINES AND DARWINIAN EVOLUTION

If Darwinian principles apply to social as well as biological entities, then we need to search for the appropriate units of selection, replication and variation at the social level. Richard Dawkins (1976) suggested the 'meme' as the answer, vaguely defined as ideas, brain patterns or behaviours. But even if it becomes fashionable, the coining of a new word does not solve the problem of explaining the mechanics of social evolution. The 'meme' beholds more problems than it gives answers.

Recent work in the philosophy of social and biological evolution (Sterelny et al., 1996; Godfrey-Smith, 2000; Hull et al., 2001) has established general definitions of the common abstract units and processes in Darwinian evolution. Developing and using these definitions, Thorbjørn Knudsen and myself (Hodgson and Knudsen, 2004b, 2006, 2010) have established that psychological or organizational entities such as habits or routines can be treated as replicators, and organizations such as business firms can be treated as 'interactors' (Hull, 1988) – the generalization of the phenotype concept in biology. This work brings us closer to a 'genetics' of social evolution, but the detailed mechanisms involved are very different from those found in the biological domain.

Generally, organisms, individuals or organizations develop mechanisms to acquire, retain and enact relatively simple heuristics or 'rules of thumb' to cope with complexity. Among such mechanisms are (biologically inherited) instincts, (culturally inherited) habits and (culturally transmitted) routines within organizations. These 'simple heuristics that make us smart' (Gigerenzer and Todd, 1999) economize hugely on both memory and computational capacity, and they can be replicated relatively easily. A disadvantage is that they are relatively rigid and difficult to adjust. The more complex and adaptive entities develop higher-order habits or routines to scrutinize lower-order habits or routines. In society as well as nature, a further means by which instincts, habits or routines adjust in a population of entities is by the selective demise of organisms, individuals or organizations that fail to adapt to their environment, or to discover or create suitable niches for survival.

In sum, the Darwinian approach provides an over-arching framework for further theoretical and empirical exploration into the detailed mechanisms involved in learning, knowledge transfer, organizational competition, and organizational change.

Note that complexity comes into this account in at least two important ways. Accounts of complex adaptive systems rightly emphasize the complexity of the interactions between entities, the existence of emergent properties as a result of their interaction, and the unpredictability of outcomes. This is complexity largely from a macro perspective.

Less prominent in the complexity literature are discussions of the complexity facing agents and the psychological or other mechanisms that are required to deal with it. In the approach to social evolution summarized here, individual habits and organizational routines are different replicators and part of the multi-level evolutionary process in society.

In a Darwinian framework, social evolution is addressed simultaneously from both a macro and a micro perspective. This dual micro-macro approach raises new questions concerning complexity. Both natural and social evolution have led to the emergence of highly complex phenomena. In human society in particular the complexity of social organization has increased vastly in the last few hundred years.

We know that in the biological sphere genetic information changes only very slowly. By contrast, habits are much more malleable. Individual habits can be formed in response to institutional and cultural circumstances. This is a version of 'reconstitutive downward causation' where system properties lead to changes in individual dispositions and capacities (Emmeche et al., 2000; Hodgson, 2003; Hodgson and Knudsen, 2004a).

A relevant question is what are the characteristics of replicators that permit such an increase of complexity in the system as a whole? An attempt to answer this question is in another paper (Hodgson and Knudsen, 2008). This paper argues that to enhance the potential for complexity in the system, the replicator must store instructions to guide the development of the relevant interactor. Consequently, the approach outlined here has a 'positive heuristic' that lays out new research questions and begins to provide some answers.

Such micro aspects of 'complex adaptive systems' are given less emphasis in much of the previous complexity literature. It is necessary to acknowledge that such systems are composed of populations of entities that face problems of complexity and survival in their local environments. Darwinism provides a meta-theoretical framework for beginning to analyse such systems from both a macro and a micro perspective. It does not provide all the answers and it always requires specific auxiliary theorizing at every level. That is part of the beauty of Darwinism; it provides a multi-level, micro-macro perspective that does not claim to explain or predict everything. Yet with such complex population systems the Darwinian principles of inheritance, variety and selection are unavoidable.

It is no exaggeration to claim that Darwin is one of the earliest and most important theorists of complexity.

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35

Economics, Management and Complex Systems

Paul Ormerod

INTRODUCTION

There are several key features of complex systems which indicate that the economy is best analysed from the perspective of complexity science.

Perhaps the single most important feature is that the macroscopically observable properties of a complex system emerge from the interactions of its constituent parts. In the context of economics, this implies that there is a need in any theoretical model for micro-foundations. In other words, a need for rules which describe the behaviour of the individual agents in the system, even when it is the macro properties of the system in which we are interested.

This view is shared by conventional economic theory, but the focus of such theory is to describe equilibrium situations. It is in essence a system of thought which is antithetical to the principles of complexity.

A further feature is a low (or even zero) ability to predict the state of the system at any given point in the future. There may very well be stable statistical distributions which describe the range of behaviours of the macroscopic factors, so that we can reasonably estimate the proportion of time which the system spends in any particular state. But we cannot predict consistently at particular points in time with any reasonable accuracy.

An important implication of this is that the understanding which individual agents have of the world is inevitably imperfect. They cannot be ascribed the cognitive powers of gathering and processing information which exist in conventional economic theory. This fits in very well with developments in economics itself in the late twentieth/early twenty-first centuries.

From the conventional paradigm of the fully rational agent with full information and using a universal behavioural rule of maximization, economics initially relaxed the assumption of full information, creating the concept of bounded rationality. Now, experimental and behavioural economics point to the use of limited information and rules of thumb, each one customized to particular circumstances

A final feature is that complex systems will typically exhibit multiple possible histories. By definition there can only ever be one actual history, but at any point in time the system has the potential to move in a variety of different ways.

A methodology which inherently captures these features is that of agent-based modelling with the agents connected on a network. Ideas/behaviour spread are contained across the network, which may either be fixed or may evolve.

The next section considers agent behaviour and whether the assumption of economic rationality can be justified. The third section discusses the inherent predictability of key macro-economic variables, and the fourth section presents evidence on non-Gaussian outcomes in the social sciences. The final section examines aspects of firm behaviour from a complex systems perspective, including an illustrative example of an agent based model with interacting agents.

HOW DO AGENTS BEHAVE?

Rationality

The understanding which individual agents have of the world is inevitably imperfect. They cannot be ascribed the cognitive powers of gathering and processing information which are implicit in conventional economic theory, even when agents are operating under bounded rather than full rationality.

The assumption of full rationality requires all agents to be able not only to gather *all* relevant information prior to making a decision, but to then be able to process it in a way which enables an agent to make the best possible decision for him or her, given a fixed set of tastes and preferences. The concept of bounded rationality relaxes only one of these key features of agent cognition, namely that of the possession of all relevant information. Agents are still presumed to take the optimal decision given the set of information available to them.

There is now a very large literature in the field of experimental/behavioural economics. The work of the 2002 Nobel Prize winners, Vernon Smith and Daniel Kahneman,[1] makes clear that in general agents do not behave according to the postulate of economic rationality. Kahneman, for example, states unequivocally in his Nobel lecture that 'humans reason poorly and act intuitively'.

Their conclusions are reinforced by, for example, the 2010 book by Bardsley et al., *Experimental Economics: Rethinking the Rules*.[2] The six authors all have distinguished pedigrees in experimental economics. Two in particular, Loomes and Sugden, have been involved with this research programme almost from its very outset some two decades ago. The book provides a comprehensive list of almost 500 scholarly references which ranges across the entire field of experimental economics.

Many of the key results were discovered in fairly simple experiments in the early years of the whole enterprise of experimental economics. For example, consumer preferences appear in general to be non-transitive. In other words, if I prefer A to B and B to C, then transitivity requires me to prefer A to C. But this logical postulate is frequently not observed in reality. Further, agents' decisions are influenced by irrelevant alternatives. In other words, preferences expressed by agents between a set of alternative choices can be influences by the introduction into the set of an alternative which is worse than any of the alternatives already on offer. So, for example, introducing a product which has both a higher price and worse quality than existing products can affect the decisions which people make. Preference reversal is widespread, in other words the preference ordering of a pair of alternatives depends on the process used to elicit the preference. These are just some of the examples, all of which violate key assumptions of conventional economic theory.

Despite the existence of this large amount of empirical evidence, the postulate of rationality is still held widely in the economics profession. There are many reasons for this, but it is useful to reflect upon just one in the current context. The recent financial crisis, for example, was simply not anticipated by the central banks, Treasuries and international institutions around the world. This theme is picked up again below in more detail. But how can this be, we might ask, if agents are presumed to form expectations about the future in a rational way? This question is dealt with easily by the true believer.

Rational expectations do not require that an agent's predictions about the future are always correct. Indeed, such predictions may turn out to be incorrect in every single period, but still be rational. The requirement is that on average over a long period of time, expectations are correct. Agents are assumed to take into account all relevant information, and to make predictions which are on average unbiased. Deviations from perfect foresight in any given period are an inherent feature of this behavioural postulate, but such deviations can only be random. If there were any systematic pattern to the deviations, the agent would be assumed to incorporate the pattern into his or her expectations. Again, on average over a long period, such expectations are correct.

It will be apparent that the theory is difficult to falsify to someone who really believes in its validity. Even the most dramatic failure to predict the future, such as the 2008 financial crisis, can be explained away as a random error. A rational expectations enthusiast can still continue to maintain the correctness of the theory by simply assuming that over some (theoretically indeterminate) period of time, on average agents' expectations prove accurate.

An assumption of the theory is that, as part of the set of information being processed, the agent is in possession of *the* correct model of the economy. Indeed, on the logic of the theory itself, if the model being used to make predictions were not correct, the forecasts would exhibit some sort of bias, some systematic error, and agents would realize that it was wrong.

It might reasonably be argued that it is difficult to subscribe to the view that agents understand the correct model of the economy given that economists themselves differ in their views as to how the economy operates. For example, in the autumn of 2008, many prominent American economists, including a number of Nobel Prize winners, vigorously opposed any form of bail-out of the financial system, arguing that it was better to let banks fail. Others, including decision makers at the Federal Reserve and Treasury, took a different view entirely.

The response of the academic mainstream has been to insist that there have been strong moves towards convergence within the profession on opinions about macroeconomic theory. By implication, anyone who takes a different view and is not part of this intellectual convergence is not really a proper economist. Olivier Blanchard, Chief Economist at the International Monetary Fund, published an MIT discussion paper in August 2008[3] on the state of modern macroeconomics. He concluded 'the state of macro is good'. The state of macro is good! Just three weeks before the financial crisis nearly brought capitalism to a halt!

Game theory

An important strand in modern economics is game theory. Uncertainty surrounds most economic decisions, and game theory appears to be an attractive way of dealing with it. In certain very limited contexts game theory and the concept of Nash equilibrium can be useful. Players, whether people, firms or governments are assumed to act rationally and seek to find a strategy that means that they themselves are as well off as they can possibly be, given how everyone else is behaving. Consider, for example, the game of noughts and crosses.[4] The outcome of this game should always be a draw since most combinations of moves will lead to this conclusion. In technical terms, the game has multiple Nash equilibria.

But beyond the confines of children's games, the concept of game theory is much less useful. Substantive assumptions about the pay-off matrix must be made before game theory can even begin to offer an account of any real world situation. The informational demands placed on agents by this are, of course, such as to render game theory useless in most practical situations.

More simply, in real life people do not appear to recognize Nash equilibrium strategies. A clear example of how an apparently simple game proves hard to play in practice is given by the *Price is Right*, a very popular television game show in America and many other countries. The rules are very straightforward and easy to remember. In other words, players have full knowledge of the rules. At all times, each player knows the state of the game. In addition, we can be sure that all those who actually get to play the game on television are devotees. They will have previously watched many previous episodes, shouting out advice or derision at the contestants from the comfort of their television rooms at home, and have had every opportunity to consider good strategic moves.

Tenorio and Cason (2002),[5] worked out analytical solutions for the Nash equilibrium strategy in *every* possible play in the game. Even more interestingly, they went on to compare these with the outcomes of what actual players did in some 300 editions of the programme. They discovered that, except where the Nash strategy is trivially obvious as it is, for example, in noughts and crosses, most of the time most of the players did not find it. Sometimes, their actual strategies were far removed from the optimal Nash decision.

The Price is Right is not a difficult game. The dimension of the problem might not seem to be large *a priori*. The rules are clear. There is no uncertainty about the situation in which a decision has to be made. Each contestant is in possession of full information about it. Yet in practice, people with every incentive to succeed, usually failed to compute the Nash equilibrium.

The disjuncture between how people ought to behave according to game theory and how they actually do behave is not a modern discovery. As Philip Mirowski makes clear in his book *Machine Dreams*,[6] experiments at RAND established this almost as soon as games such as the Prisoner's Dilemma had been invented over 50 years ago. Indeed, Merrill Flood, its inventor, soon abandoned work on game theory altogether for exactly this reason.

Two examples will suffice. Flood offered RAND secretaries a choice. One of them was given the option of either receiving a fixed sum of money ($10, say), or receiving a total of $15 provided that agreement could be reached with another secretary as to how this money was to be divided between them. One Nash solution is that the two split the marginal difference. In other words, they divide the extra $5 between them so that they get $12.50 and $2.50 respectively. Obstinately, in practice most secretaries appealed not to the new idea of the Nash equilibrium but to the concept of fairness, as old as humanity itself. They divided the total amount exactly equally, $7.50 each.

The second is even more interesting. Flood carefully devised a pay-out system in the Prisoner's Dilemma in which the best option for both players was not the usual co-operative one. The Nash equilibrium was unequivocally for both players to defect. To play the game, he recruited distinguished RAND analysts John Williams and Armen Alchian, a mathematician and economist respectively. They were to play 100 repetitions of the game. They each knew about von Neumann's work, but not about the Nash equilibrium, which had only just been discovered. Both were asked to record their motivations and reactions in each round.

The Nash equilibrium strategy ought to have been played by completely rational individuals 100 times. It might of course have taken a few plays for these high-powered academics to learn the strategy. But Alchian chose co-operation rather than the Nash strategy of defection 68 times, and Williams no fewer than 78 times. Their recorded comments are fascinating in themselves, and a single aspect will have to suffice us here. Williams, the mathematician, began by expecting both players to co-operate, whereas Alchian the economist expected defection. But as the game progressed, co-operation became the dominant choice of both players.

In other words, even leading academics who had been involved in game theory research, but who were not yet aware of the newly discovered concept of the Nash equilibrium, behaved most of the time in a way contrary to the predictions of Nash's theory.

Nash was immediately told of these results, and his reaction is quoted at length by Mirowski. Many of the points are technical, but the most dramatic by far is the following: 'It is really striking how inefficient the players were in obtaining rewards. One would have thought them more rational'. In other words, his theory predicted a particular kind of behaviour. The players did not follow it and, clearly, the mistake lay with them and not the theory. Two very clever people, intimately familiar with game theory in general, had persistently chosen a non-Nash strategy. But the theory simply could not be wrong, because that is how rational people ought to behave!

HOW PREDICTABLE IS THE ECONOMY?

Most of the results above relate to individuals. Could it be the case that institutions such as central banks, the International Monetary Fund or national Treasuries have knowledge which is superior to that possessed by the typical individual?

Certainly, the track record of forecasting macroeconomic variables such as next year's growth in GDP does not suggest any special knowledge on the part of the authorities. For example, at the start of 2008, decent growth was predicted both for Europe and the US in 2009.[7] Even as late as August, the general view was that there would still be positive growth in 2009. But in fact, the West was already in recession in August 2008!

This was not simply a one-off error in an otherwise exemplary forecasting record. The major crisis in East Asia in the late 1990s was, for example, completely unforeseen. In May of that year the International Monetary Fund (IMF) predicted a continuation of the enormous growth rates which those economies had experienced for a number of years: 7% growth was projected for Thailand in 1998, 7.5% for Indonesia and 8% for Malaysia. By October, these had been revised down to 3.5, 6 and 6.5% respectively. But by December the IMF was forecasting only 3% growth for Malaysia and Indonesia, and zero for Thailand. Yet the actual outturns for 1998 for these countries were spectacularly worse, with output not growing but falling by large amounts. The fall in real GDP in 1998 was –10% in Thailand, and –7 and –13% in Malaysia and Indonesia respectively.

Over the past 40 years in particular, a track record of forecasts and their accuracy has been built up. Economists disagree about how the economy operates, and these disagreements are reflected in, amongst other things, the specification of the relationships in macro-economic models. But, over time, no single approach has a better forecasting record than any other. Indeed, by scientific standards, the forecasting record is very poor, and a major survey of macro-economic forecasting[8] concluded that there is no real evidence which suggests that accuracy has improved over time.

As examples of the one-year ahead forecasting record for GDP growth, for the US economy recessions have not generally been forecast prior to their occurrence, and the recessions following the 1974 and 1981 peaks in the level of output were not recognized even as they took place.[9] In general, the forecasting record exhibits a certain degree of accuracy in that the average error over time is smaller than the size of the variable being predicted. But the error is still large compared to the actual data, and most of the accurate forecasts were made when economic conditions were relatively stable.

As long ago as the 1920s, Irving Fisher, the most distinguished American economist of the early decades of the twentieth century, argued that the business cycle – the short term fluctuations in GDP growth – is inherently unpredictable. He believed that movements over time in the volume of output were 'a composite of numerous elementary fluctuations, both cyclical and non-cyclical' (*Journal of the American Statistical Association*, 1925) and quoted approvingly from his contemporary Moore, who wrote that 'business cycles differ widely in duration, in intensity, in the sequence of their phases and in the relative prominence of their various phenomena'.

In such circumstances, it would be virtually impossible to distinguish this type of data from data which was genuinely random in terms of its predictability. There are too many factors, and not enough data with which to identify their separate impacts. As noted above, the actual macro-economic forecasting record is certainly compatible with this view.

Ormerod and Mounfield (2000) formalized Fisher's insight.[10] Essentially, they formed a delay matrix of time-series data on the overall rate of growth of the economy, with lags spanning the period over which any regularity of behaviour is postulated by economists to exist. They used methods of random matrix theory to analyse the correlation matrix of the delay matrix. This was done for annual data from 1871 to 1994 for 17 economies, and for post-war quarterly data for the US and the UK. The properties of the eigenstates of these correlation matrices are similar, though not identical, to those implied by random matrix theory. This suggests that the genuine information content in economic growth data is low, and that the time-series data on GDP growth is very similar to genuinely random data.

The poor forecasting record of GDP growth by economists appears to be due to inherent characteristics of the data, and cannot be improved substantially no matter what economic theory or statistical technique is used to generate them. Over what is thought of as the time period of the business cycle in economics, in other words the period over which any regularity of behaviour of the growth of GDP might be postulated to exist, the genuine information content of correlations over time in the data is low.

The same technique can be applied to the *change* in the inflation rate, and the results are qualitatively very similar. Monetary authorities such as the Bank of England and the European Central Bank are each set a target rate of inflation which they have to try to achieve by the manipulation of short-term rates of interest. But the rate of inflation in, say, a year's time is inherently unpredictable. Indeed, we do not even know whether it will be higher or lower than it is at present, given that the changes in inflation are very similar to purely random data. So the monetary authorities are essentially attempting to target and control a random variable.

The conventional approach to the control of the economy at the aggregate level requires the ability to:

- make reasonably accurate predictions of what will happen in the future in the absence of policy changes
- have a reasonably accurate understanding of the impact of policy changes on the economy.

Neither of these is the case. There are inherent reasons why the ability to forecast with any reasonable degree of accuracy over time is severely limited, and why the ability to extract information from aggregate time-series data about the ways in which economic variables interact is also restricted.

Short-term lack of predictability is of course a key feature of complex systems.

POWER LAWS AND NON-GAUSSIAN OUTCOMES

A second key characteristic is correlated behaviour amongst the individual agents of the system, which gives rise to distinctly non-Gaussian outcomes for the system as a whole.

There is a literature, stemming from the physical sciences, which tries to fit a particular kind of distribution, namely a power law. Before moving to a more general discussion of this, it is important to clarify a confusion which sometimes arises in fitting such relationships.[11] We often observe relationships reported between the size of an event and its ranking. So, for example, Zipf[12] reported a relationship between the number of times a given word is observed in a language and its rank number when all words are ranked by size. Given a variable y which orders a set of data by the size of the individual observations and the rank of each observation in this ordering, r, if the data follows a power law distribution, we will observe the relationship: $y = r^{-\beta}$. We might equally, however, examine not the size/rank relationship but the frequency distribution. In terms of the distribution of high-income earners, for example, we could perform a regression with the Zipf relationship so that a given income is proportional to the ranking of that income in the data set, or we could regress the number of people whose income is higher than this on income. But the two regressions[13] are simply different ways of looking at the same thing.

Perline[14] offers a detailed critique of the claim that power laws characterize many data sets in the social sciences. He notes that findings are often represented as though data conformed to a power law form for all ranges of the variable of interest. Perline refers to this ideal case as a *strong* inverse power law (SIPL). However, many of the examples used by Pareto and Zipf, as well as others who have followed them, have been truncated data sets, and if one looks more carefully in the lower range of values that was originally excluded, the power law behaviour usually breaks down at some point. This breakdown seems to fall into two broad cases, which Perline calls here *weak* and *false* inverse power laws (WIPL and FIPL). WIPL refers to the situation where the sample data fit a distribution that has an approximate inverse power form only in some upper range of values. FIPL refers to the situation where a highly truncated sample from certain right-skew (and in particular, 'lognormal-like') distributions can convincingly mimic a power law. His paper shows that the discovery of Pareto–Zipf-type laws is closely associated with truncated data sets. Further, through detailed analysis of some reported results, he concludes that many, but not all, Pareto–Zipf examples are likely to be FIPL finite mixture distributions and that there are few genuine instances of SIPLs.

The problems of truncation in data sets are particularly acute. For example, as Perline observes 'it is in the nature of things the low end, or very commonly, all but the upper tail, of many kinds of data is hidden because of definitional fuzziness and the difficulties associated with measurement below some threshold. At the same time, it is frequently the high end that is most important or most likely to capture our attention'.

The reasons why power laws are particularly attractive to the physical sciences, whilst important, are nevertheless a diversion to the themes of this chapter, and the interested reader is referred to the Wikipedia entry on power laws for a clear introduction to this topic.

However, there is a fundamental difference between physical systems and human and social systems. In the latter, the component parts, the agents, can act with purpose and intent, unlike the component parts of the former, the particles.

As a modelling strategy, there is a great deal to be said for taking the 'particle' model as the 'null model'. In other words, to set up a model in which the agents by definition have zero cognition, with no ability to gather or process information or to learn from the past. We initially see how far this model takes us, how far it is able to account for the phenomena under investigation, before starting to make it more realistic by ascribing weak cognitive powers to agents. This concept is discussed in much more detail in Bentley and Ormerod (2010).[15] The contrasting approach of the standard social science model is to posit the fully rational agent as the null, and then make agents slightly less smart if the model needs to be refined.

A particular success with the 'zero intelligence' agent approach is reported by Farmer et al.[16] They use data from the London Stock Exchange to test a simple model in which minimally intelligent agents place orders to trade at random. The model treats the statistical mechanics of order placement, price formation, and the accumulation of revealed supply and demand within the context of the continuous double auction and yields simple laws relating order-arrival rates to statistical properties of the market. They test the validity of these laws in explaining cross-sectional variation for 11 stocks. The model explains 96% of the variance of the gap between the best buying and selling prices (the spread) and 76% of the variance of the price diffusion rate, with only one free parameter.

There are, however, few such examples and better models are usually obtained when a small amount of cognitive ability is ascribed to the component parts. The implication is that in the social science we should not have the same fixation with trying to discover power law properties at the system level. What *is* significant, however, is that we observe very generally right-skewed (heavy tailed), distinctly non-Gaussian.

For example, Ormerod (2010)[17] examines both the duration and size of economic recessions in 17 Western economies using annual data over the period 1870 to the present. Two definitions of recession are used. First, the duration of a recession is the number of consecutive years in which real GDP growth is less than zero. The size of a recession is the cumulative percentage fall in GDP during these years. Second, a recession is defined as a period of successive years during which the level of real GDP remains below its previous peak. The size of this definition is the cumulative sum of the percentage differences between the level of GDP in each of the recession years and the level of GDP at its previous peak.

On either definition, most recessions are very short, lasting only one year in around two-thirds of the cases. Power law fits to the data give relatively poor approximations, and both the size and duration of recessions are more clearly exponential. Two approaches were used to calibrate both the exponential and the Weibull distributions to the size data. First, estimation by nonlinear least squares of the appropriate functional form. Second, a grid search of the parameters which maximize the p-value at which the null hypothesis that the actual data and the theoretical distribution are the same, again using the Kolmogorov–Smirnov test.

On both definitions of a recession and using both statistical approaches, the data are best approximated by the Weibull distribution with shape parameter less than one, indicating the probability of exit from recession is reduced as duration and size are increased. This is consistent with Keynes' concept of 'animal spirits', of the sentiment of agents, becoming depressed.

There are now many examples of right-skewed distributions in the social sciences, regardless of whether they are strong, weak or false inverse power laws in the sense of Perline discussed above. All the data sets share the property that their distributions, whatever they may be, are distinctly non-Gaussian. This has been known to be a feature of the distribution of income and wealth since the time of Pareto around 1900. Decisive evidence on the right-skew distribution of firm sizes, for example, has been both available and well known in industrial economics for many years.[18] Plausible candidates in the economics literature to represent the empirical size distribution are the lognormal, the Pareto and the Yule. The main problem is in capturing the coverage of small firms. Recent attempts to do this, such as on the population of US firms,[19] lend support to a power-law distribution linking firm sizes probability densities with the size ranking of firms. However, this may well be an as yet unexplained outcome of aggregation, because the findings seem not be robust with respect to sectoral disaggregation.[20]

An innovative finding by econophysicists is that the variance of firm growth rates falls as firm size increases, although this too was anticipated in the early 1960s.[21] A further discovery is that the size-frequency relationship which describes the pattern of firm extinctions appears to be very similar to that which describes biological extinctions in the fossil record.[22]

MODELLING FIRM BEHAVIOUR

Empirical evidence

An excellent insight of life inside a giant firm is given in Marlin Eller's book *Barbarians Led by Bill Gates*.[23] Eller was from 1982 to 1995 Microsoft's lead developer for graphics on Windows. Eller's introductory remarks are worth quoting at some length: 'There was a great disconnect between the view from the inside that my compatriots and I were experiencing down in the trenches, and the outside view … in their quest for causality [outsiders] tend to attribute any success to a Machiavellian brilliance rather than to merely good fortune. They lend the impression that the captains of industry chart strategic courses, steering their tanker carefully and gracefully through the straits. The view from the inside more closely resembles white-water rafting. "Oh my God! Huge rock dead ahead! Everyone to the left! NO, NO, the *other* left!"'. Eller goes on 'reality is rarely a simple story and is probably more like a *Dilbert* cartoon'.

The experience of Microsoft illustrates much more general points about the behaviour of firms within the complex system which is the economy. Windows now of course dominates the PC operating systems world. But its success was based far more on a series of accidents than on a far-sighted, planned strategy.

In the late 1980s, the main strategic goal of Microsoft was to link up very closely with IBM. In particular, the two companies were developing jointly a new operating system, OS/2. Windows merely limped along. Bill Gates staged a major publicity coup at the computer industry's biggest exhibition, COMDEX, in 1983. He announced that Windows 1.0 would be shipped in the spring of 1984. After immense effort, it finally appeared in November 1985. The reviews were blistering. The product size was huge relative to the capability of the personal computers which then existed. The *New York Times* observed that 'Running Windows in 512K of memory is akin to pouring molasses in the Arctic'. In Eller's blunt description: 'the product was essentially useless'. The support team within Microsoft for Windows was cut back to a mere three people.

In contrast, great effort was being put into the relationship with IBM. In October 1988, the two companies launched OS/2 Presentation Manager, with Bill Gates proclaiming '[this] will be the environment for office computing in the 1990s'. Marlin Eller quotes Steve Ballmer, Gates's number two, as saying 'This is it, after this we're not going to have any more Windows. It's all OS/2'.

Windows 2 meanwhile had been launched, with little success. Only a couple of people were left within Microsoft to maintain the product. Sporadic development of the product still took place on the next version, Windows 3.0. But an article in the *National Review* summed up the view of the industry 'Microsoft would cease development of its Windows software after the release of Windows 3.0 … IBM's OS/2 would become the main PC operating system for the 1990s'.

On 22 May 1990, Windows 3.0 was made available to the public. It sold 2 million copies in the first six months.

The point is that, despite the enormous business abilities of Gates and his key players, they did not foresee that it would be Windows and not OS/2 which would fulfil this role. Windows was almost abandoned as a stand-alone product. Its support team was cut to virtually zero. And it proved a massive, overwhelming success. Success, like failure, comes in many guises.

It is the sheer complexity associated with many decisions which defies the orderly application of the rational calculation of economic theory. The number of possible permutations of outcomes is simply too great to be computed. The degree of uncertainty rarely permits the computation of the optimal, the unequivocally best strategy at any point in time.

A further practical illustration of the complex nature of the system in which firms operate is provided by Marc Levinson's book[24] on how the humble shipping container transformed the world. Almost 50 years ago, in April 1956, a refitted oil tanker made the first ever container voyage from Newark to Houston.

From this modest start, the container has revolutionized economic geography, devastating traditional ports such as New York and London and enabling massive growth in obscure ones like Oakland and Felixstowe. Shipping costs have fallen so dramatically that the structure of world trade itself has been altered. Most trade used to be raw materials or finished products. Now it is mainly intermediate goods, with manufacturers able to source from almost anywhere, thanks to cheap transport costs. In turn, this has facilitated the massive economic growth of Asia. The container has enabled global supply chains and just in time production to become routine.

The most powerful and general insight of the book is set out in the final chapter: 'time and again, even the most knowledgeable experts misjudged the course of events ... almost nothing [the container] touched was left unchanged, and those changes were often not as predicted'.

For example, the leader of New York's longshoremen warned in 1959 that containers would eliminate 30% of his members' jobs. Within 15 years, three quarters of them had disappeared. Even the inventor of the container himself, Malcolm McLean, made colossal misjudgements. At the time of the 1973/74 oil price shock, he had just ordered a new fuel-guzzling fleet, and he built a new squadron of slow but fuel efficient ships just before fuel prices fell sharply in the 1980s.

Governments in New York, San Francisco and Britain invested heavily in reconstructing traditional ports, yet the investment was obsolete almost before the last of the concrete had dried. Top American economists predicted that containerization would be good for manufacturing in the metropolitan North Eastern states, enabling them to ship more cheaply to the South than could the landlocked Midwest. No one foresaw that the collapse in transport costs would enable entirely new competitors from elsewhere in the world to decimate the region's traditional industries.

This massive uncertainty about the future is an inherent feature of the world, which permeates both public and private sector decision making. Carroll and Hannan[25] take an ecological approach to understanding firms, and provide many interesting illustrations. A hundred years ago, for example, in the first two decades of the twentieth century, over 2,000 firms attempted to make cars for the new American market. Over 99% of them failed.

The endorsement of the book by Oliver Williamson, 2009 economics Nobel Laureate, brings out a further key point from their empirical examples: '... the authors adopt a demographic perspective in which variety among firms within industries becomes the object of analysis. Vitality resides in the differences – which has important ramifications for organization theory and for public policy toward business'. In other words, a key empirical feature of firms is their diversity. In the jargon of economics, the agents are heterogeneous. To non-economists, this may seem blindingly obvious, but the theoretical model of the 'representative agent', the single agent whose behaviour can proxy that of all agents in the economy, survives strongly in mainstream economics.

Failure and extinction

Failure and extinction is in fact a pervasive feature of firms, and one which is almost entirely neglected by mainstream economic theory. On average, just over 10% of all firms, both in the US and Europe, become extinct in any given year. And even giant firms fail. Modern examples include Enron, WorldCom and of course Lehman's. Evidence on this is provided by the British economic historian Les Hannah[26] and by the American sociologist Neil Fligstein.[27]

Fligstein's evidence is less detailed than Hannah's for our immediate purposes, though it contains much interesting material. His data set does not include evidence on whether a firm failed completely and ceased to exist as an independent entity. Rather, it focuses on whether or not a company was in the list of the largest 100 American firms at the end of each decade from 1919 to 1979. Only 33 out of the top 100 in 1919 remained in the list in 1979, and since then the attrition amongst the 1979 survivors has continued.

Fligstein notes that no fewer than 216 companies in total made it into the American Top 100 over the 60 year period. Some, such as Bethlehem Steel, WF Woolworth, Chrysler and Goodyear Tire and Rubber were in the list for the entire period. Others enjoyed their 15 minutes of fame in a single appearance, such as Atlantic Gulf and West Indies Shipping Line in 1919, Lehigh Valley Coal in 1929, Climax Molybdenum in 1939, Allied Stores in 1949, Kaiser Steel in 1959, International Utilities in 1969 and, anticipating the future, Rockwell International in 1979. International Business Machines (IBM) makes its first appearance in 1939, but otherwise computing firms such as Microsoft are absent, simply because for the most part they barely existed at the last date on Fligstein's list, 1979.

On average, over the individual decades from 1919–29 to 1969–79, 78 out of the top 100 at the start of any decade were still there at the beginning of the next. But no fewer than 22 out of 100 were not. These are, or rather in most cases were, the giants of American capitalism. Operating on a massive scale, and possessed of enormous resources, almost one in every four were unable to remain in the top 100 for more than a decade.

Hannah traces the survival of the world's 100 largest industrial companies in 1912 through to 1995. The companies in the world's top 100 in 1912 represented the cream of capitalism. These were the survivors of a brutal era of competition, and had successfully survived the massive wave of mergers around the turn of the century. As Hannah points out 'They were, on the whole, firms that contemporary stock market analysts considered attractive and safe because of their consistently reliable record of generous but sustainable dividends. A population of the largest firms of 10 years earlier would almost certainly show earlier exits and faster rates of decline than this population'.

Yet within 10 years, no fewer than 10 of these companies had disappeared. Over the course of the twentieth century, 29 became bankrupt and in total 48 disappeared. Of the 52 survivors, only 29 remained in the world's top 100 in 1995. Hannah notes laconically, 'the tendency to over-emphasise successes, and to rationalize them *ex post* is chronically endemic amongst business historians and management consultants'. The latter group are particularly prone to the temptation of claiming to have found the unique formula for business success. Books proliferate, and occasionally sell in very large numbers, which claim to have found *the* rule, or small set of rules, which will guarantee business success. But business is far too complicated, far too difficult an activity to distil into a few simple commands, or even some of the more exotic exhortations of the business gurus.

Firms certainly act with purpose and intent, and have no intention of failing. But the complexity of the environment in which they are operating means that it is as if they were operating much closer to the zero intelligence particle model of agent behaviour than to that of the fully rational agent.

An illustrative agent-based complex adaptive systems model

An example of a complex systems approach to modeling key aspects of firms which uses the 'zero intelligence' model of behaviour is given by Ormerod and Rosewell.[28]

The methodology used here, that of computer simulation of an agent based model, is the standard way of modeling complex systems in the social sciences. Conventional economics remains constrained by its insistence on obtaining analytical solutions to sets of equations. Analytical solutions are nice to have if you can get them, but they act as serious constraints on the types of model which can be built. Partial differential equations are, for example, routinely solved by numerical algorithms rather than brain power being wasted in an effort to obtain an analytical result. We have all moved beyond using the abacus or slide rule to perform calculations, and so we should embrace computer simulation as the best way to make progress in the social sciences.

There are two key 'stylized facts' at the system level which the model attempts to replicate. First, it has been known for some time that the probability of extinction is highest in the early life of a firm, but declines rapidly and is thereafter more or less invariant with respect to the lifespan of the firm.[29] Second, it has been shown recently, that the empirical relationship between the frequency and size of firm extinctions is described well by a power law,[30] very similar to that observed in the palaeontological record of the extinction of biological species.[31]

The model contains N agents, and every agent is connected to every other. The model evolves in a series of steps. The rules of the model specify, (a) how the connections are updated, (b) how the fitness of each agent is measured, (c) how an agent becomes extinct, and (d) how extinct agents are replaced. The overall properties of the model emerge from the interactions between agents. The connections between agents can be thought of as representing the way in which the net impacts of the overall strategies of firms impact on each other. Both the strength and the signs of the connections vary. Each firm can be thought of as attempting to maximize its overall fitness level. In the model, the firm proceeds by a process of trial-and-error in altering its strategy with respect to other firms. The model is solved over a sequence of iterated steps, and at each step, for each agent one of its connections is chosen at random, and a new value is assigned to it.

Despite the fact that firms are postulated to act at random, the system wide properties which emerge from the model are very similar to those observed empirically on the distribution of firm extinctions with respect to age, and on the relationship between the frequency and size of extinctions.

After establishing this initial level of confidence in the model, Ormerod and Rosewell go on to add successively greater levels of purpose and intent to the behaviour of firms, and see how far this process can go. They find that there are very considerable returns to acquiring knowledge, for even a small amount leads to a sharp increase in the mean agent age at extinction for agents with knowledge compared to those without. Indeed, they find that as both the amount of knowledge available to firms increases and as the number of firms capable of acquiring such knowledge rises, the lifespan of agents begins to approach the limiting, full information paradigm of neo-classical theory in which agents live for ever.

However, even with relatively low levels of knowledge and numbers of agents capable of acquiring it, the model ceases to have properties which are compatible with the two key stylized facts on firm extinctions. The clear implication is that firms have very limited capacities to acquire knowledge about the likely impact of their strategies.

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36

How Complexity Science is Transforming Healthcare

Brenda Zimmerman

INTRODUCTION

Healthcare in Western societies is at a turning point. The enormous medical and public health advances of the last half century have extended life spans and improved quality of life for millions of people. The costs, however, have had an equally rapid ascent, leading many to believe we have created an unsustainable system. Personalized medicine, the subject of science fiction only a few years ago, has increasingly become a reality. One's genetic and proteomic profiles can be used to predict and treat diseases with an individually tailored approach. Paradoxically, population based health concerns, which address the health needs not of individuals but of large groups (or populations), have become increasingly important to understand how to improve the health status and quality of life across communities, countries and continents. Personalized medicine and population health are putting further demands on an already strained healthcare system.

What does complexity science offer to this stressed system? In the UK, USA and Canada, members of the healthcare sector are looking to complexity science for insights to address the public policy, clinical and management challenges of healthcare. For policy makers, complexity science provides a new way to understand public policy as being coherent across populations while, at the same time and paradoxically, 'inconsistent' in application because it allows for variation in response to local needs. This creates tensions for public policy makers which have often seen coherence and consistency as synonymous just as equity and equality have often been taken to mean the same. In practice, the National Health Service (in the UK) has used design principles inspired by complexity science (hereafter 'complexity principles' in their redesign of the delivery of healthcare; while the Institute of Medicine (in the USA) has drawn upon complexity science to understand and address quality shortcomings in healthcare delivery.

The clinical applications of complexity science range from relationship-centered care to using fractal geometry for diagnosis and treatment of cardiac conditions. In practice, most of the clinical applications are still in their infancy but show great promise for diagnosis and treatment of a wide range of diseases, especially chronic diseases. Indeed, the Canadian Academy of Health Sciences in 2009 chose complexity science as its theoretical frame for the study of chronic disease management.

In terms of health care management and leadership of health care organizations, complexity science has been transformative in many health care organizations through understanding distributed network models of control and authority. In practice, jobs have been redesigned, care delivery modes have been altered and patient safety initiatives have applied complexity science-inspired principles to address issues such as hospital acquired infections.

Clearly, then, complexity science is impacting healthcare across the Western world. In this chapter we review three domains – public policy, clinical practice, and management of healthcare organizations – to outline how complexity science has been applied (or at least discussed) in each; and to compare the rhetoric of complexity science as a transforming force in healthcare with the reality of practice to date. We conclude by identifying some of the key challenges complexity science faces in transforming healthcare, i.e. attitudes, mindsets, traditions, and power structures.

A CONTINGENCY FRAMEWORK FOR COMPLEXITY APPLICATIONS TO HEALTHCARE

It is possible to distinguish between simple, complicated and complex contexts of human action (Zimmerman et al., 1998; Glouberman and Zimmerman, 2002; Westley et al., 2006; Snowden and Boone, 2007). Simple contexts are known *a priori* and hence are well suited to consistent applications of 'best practices'; while complicated contexts are knowable *a priori* but often require more rigorous analysis and investigation than a simple context. Because simple and complicated contexts are inherently knowable, action within them is often guided by a sense of being able to fully understand and potentially to control the system. Holman and Lorig (2000) argue that this is the case with acute illness wherein the healthcare provider can normally identify the cause and address it. They contrast this with chronic disease which, in the language of this Handbook, represents an inherently complex context for intervention because chronic diseases frequently have multiple causes, co-morbidities and morph or evolve over time. As a consequence, action is guided by a sense of inherent unknowability in complex contexts which require approaches that incorporate, in addition to the knowledge and skill of health care providers, the knowledge and skills of patients, their families and the communities in which they reside. This contingency framework of simple, complicated and complex contexts can be applied to policy and organizational issues of healthcare, in addition to clinical ones.

'COMPLEXITY PRINCIPLES' IN HEALTHCARE

There is no definitive list of complexity science-inspired principles in healthcare. In both healthcare literature and practice there is great diversity in the attention paid to the different attributes of complex systems and ensuing principles for intervening within or managing them. In this chapter, 'complexity principles' is the label used to describe a broad cadre of complex system attributes and associated management principles, for ease of reading. Some of the most common of these used in healthcare are described briefly below as they are discussed in more detail in earlier chapters of this Handbook.

- *Emergence* is the appearance of outcomes in the form of new structures, patterns or processes at the system level that are *unpredictable* from the components that created them through their interactions. In healthcare, emergence has been crucial in recognizing the role of uncertainty and surprise from each of a public policy, clinical and organizational perspective.
- *Self-organization* is order created internally through the interaction of components rather than directly by an external force or individual/

institution. Recognition of the importance of self-organization challenges the command and control paradigm which has dominated healthcare since the early twentieth century.

- *Distributed control* arises when there is no central controller for a system such that design and management of the system is distributed. A departure from most Western medical and policy approaches, intervening in contexts of distributed control requires looking at the patterns across a system and between systems rather than for searching for single point causes.
- *Feedback* is the reciprocal effect of one subsystem on another subsystem or larger system. *Negative feedback* has a dampening effect on deviations or changes whereas *positive feedback* has an amplifying effect. In healthcare, this has important implications for policy makers and clinicians as they assess their interventions and impacts.
- *Minimum specifications* are also known as *simple rules*. They refer to a small number of guidelines that typically determine the design and functioning of a complex system. This notion is used both inductively to understand what rules of interaction are shaping the current system and deductively to identify new rules of interaction which could create a healthier system (clinically or organizationally).
- *Sensitive dependence on initial conditions* (or the butterfly effect) is a property of a complex system in which small changes have a disproportionate or *nonlinear* impact. Hence the past is a crucial part of understanding the trajectory of a system. In healthcare this principle is often translated into a rationale for *context-specific* solutions.
- *Connectivity* in complex systems favors *relationship-centered* approaches to understanding and managing them because the connections or relationships between 'parts' of a system are key to its functioning. Rather than changing the parts, the focus becomes recognizing *interdependence* and connected *networks* that need to be changed.
- *Fractals* are geometric patterns (temporally or spatially) that exhibit *self-similarity* across scales, also known as *scalar invariance*. In healthcare, the recognition of fractals requires looking at data at multiple scales to diagnose problems and prescribe solutions.
- *Embedded or nested systems* refers to how systems exist within systems such that change often involves the *co-evolution* of systems. This has been extended to include *co-creation of meaning* in healthcare organizations.

This chapter will identify examples of these complexity principles across the three healthcare realms of public policy, clinical medicine and management of healthcare organizations.

COMPLEXITY AND PUBLIC POLICY FOR HEALTH

Public policy for health includes articulating objectives for the government, choosing priority areas, selecting policy instruments (e.g. legislation, budgets, contracts, etc.) as well as content, and implementing. Complexity science has something to contribute to the selection of policy instruments as well as policy design and implementation. Health policy deals both with the front-line delivery of healthcare to individual patients and with public health activities which are population based such as pandemic preparedness or reduction in rates of obesity or substance abuse. In both arenas, complexity science has started to play a role.

The Institute of Medicine (IOM) in the USA issues an annual report on the state of healthcare in America. In 2001 the report focused primarily on front-line service delivery issues. It described quality problems not merely as a gap but as a 'chasm', an enormous difference between what is delivered and what should be delivered based on resources employed and expectations of the public (IOM, 2001). The IOM described the US healthcare system as a complex adaptive system. The report used complexity principles, focusing particularly on 'simple rules' or minimum specifications, to both describe the current state of healthcare and prescribe solutions to address the quality chasm. The simple rules of behavior for the current system were derived inductively by examining the current patterns and practices of healthcare delivery and financing. To create a more cost-effective, safe, patient-centered and high quality system, these rules were turned on their head in the recommendations contained in the prescriptive sections of the report. For example, current implicit rules have the physician in charge of a patient's records and treatment decisions. The revised rules have the patient in control. The existing rules include professional autonomy allowing physicians to operate independently for the most part versus the revised rule of collaboration and continuous information flow between all care providers and the patient. The IOM was influenced by and influenced a number of independent healthcare groups concerned with quality of care such as the Institute for Healthcare Improvement which has also used the complexity principles of self-organization and simple local rules leading to emergent outcomes (see examples at IHI.org).

One of the challenges of public policy for health is the concept of planning in light of uncertainty, emergence and surprise. Many traditional planning approaches in policy across the globe focus on developing single-point forecasts or extrapolations of current trends into the future based on probability distributions (Lempert et al., 2002). With these approaches, surprise is problematic and is often downplayed or even ignored. Complexity science-inspired planning approaches using both quantitative modeling approaches and narrative scenario planning modes provide enhanced tools for policy makers dealing with conditions of deep uncertainty (Lempert et al., 2002). A goal of *prediction* of the future, which is unlikely in unpredictable emergent contexts, is replaced by a goal of *anticipation* of multiple possible futures, i.e. a perspective emphasizing the need for preparedness for multiple plausible realities. Robust strategies that can adapt to changing circumstances replace optimal strategies (Lempert et al., 2002).

In the UK, the National Healthcare Service (NHS) has applied complexity principles in their planning processes in several health trusts (regions) across the UK as well as in individual hospitals (Fraser and Greenhalgh, 2001; Plsek and Greenhalgh, 2001; Greenhalgh, 2008). Embracing the ideas of uncertainty, emergence and surprise they designed policy experiments and leadership programs for policy makers and managers in healthcare. They used primarily qualitative aspects of complexity, the metaphorical power of looking at the NHS as a complex adaptive system and applying complexity principles of simple rules, emergent outcomes and nonlinear interactions in their planning and policy making. Leadership programs based on these principles eschewed the notion of centralized control and recognized the power of self-organization and the need to focus on relationships to understand and improve healthcare systems. The reactions to these approaches in the NHS are mixed. Some argue that the knowledge of complexity has had a profound impact on how the NHS is managed (Manning, 2001; Sweeney, 2004) but others challenge whether any real impact on health care delivery to patients has been realized (Reid, 2001).

Public health, which focuses on populations rather than healthcare delivery to individuals, is often seen in a negative light within healthcare systems as distracting attention away from the more visible front-line service delivery of healthcare (Merson et al., 2006). Rather than a focus on the cure aspects of healthcare, public health is more focused on prevention of health problems. It doesn't make for front page news stories, except in the case of flu pandemics, but when public health is effective, it can have profound and long-run implications for improving the health of populations. Vaccines, which were unheard of decades ago, have all but eliminated many devastating illnesses in many countries and some diseases, like polio, have been eradicated globally through public health efforts. A decrease in smoking, largely driven by public health campaigns and programs, has dramatically reduced the rates of lung cancer in North America (Skinner, 2002: 38–39). What does complexity science add to meeting public health challenges?

Quite a bit, it turns out, as the next few paragraphs outline.

Epidemiology has long been a mainstay of public health. Tracking a virus or disease or prevalence of a condition (e.g. obesity, smoking, and substance abuse) has been central to public health. Since SARS (severe acute respiratory syndrome) and with the evolution of avian and swine influenzas, public health agencies across the globe have been focused on pandemic preparedness. Complexity science, with its focus on relationships and interdependence, challenges public health to look beyond epidemics and pandemics to *syndemics*. Whereas epidemics and pandemics look at an individual disease, virus or health factor, syndemics looks at two or more synergistically interacting diseases, viruses or health factors. The unit of analysis for syndemics is the connection between the factors or diseases. Medical anthropologist Merrill Singer coined the term syndemic in the early 1990s as he studied the patterns between linked afflictions (Singer and Snipes, 1992; Singer 1994, 1996). Syndemics explores the connections, for example, between HIV/AIDS, violence and substance abuse. Syndemics builds on epidemiology but adds a higher order dimension to the analysis. Studying a single disease alone may ignore key patterns of spread of the disease that could give insights into prevention and treatment.

In addition, syndemics points out that because of the synergistic interactions between afflictions, i.e. both biomedical and social determinants of health, some populations bear a disproportionate disease burden. Diseases are rarely evenly distributed across a population so some communities or groups are harder hit. By focusing on the distribution of diseases and how they interact with other afflictions, new prevention strategies can be discovered (Singer, 2003; CDC, 2008).

An ancient Sufi saying helps capture the essence of the syndemics approach.

> You think that if you understand one, you understand two – because one and one are two. But you must also understand 'and'.

Syndemics looks to system dynamics for the causes of diseases and uses network mapping to identify patterns in the interaction of health factors and diseases. By focusing on the 'and' in disease burdens across populations, syndemics suggests an expansive role for public health policy makers and managers.

In the province of Ontario in Canada, public health policy makers are looking to complexity science to create a contingency framework of policy interventions depending on the degree of unpredictability and the degree of variability between the contexts in which the policy will be applied (e.g. diversity in the communities or sub-populations across a region) (Touhy et al., 2009). The contingency framework is an acknowledgment that policy makers face issues that are increasingly complex; and that traditional policy making tools of centralized directives to ensure consistency, or decision tree approaches to application of legislation, do not work effectively for complex contexts with lots of interdependence, unpredictable change, emergence and self-organization.

Zimmerman and Ng (2008) present a framework that contrasts health public policy from a traditional mechanistic approach with that from a complex systems view. They noted that complexity science changes the (1) perspective, (2) planning, (3) implementation and (4) evaluation of public policy. They contrasted traditional and complexity inspired approaches to three policy challenges: national HIV/AIDS strategies, regional nursing shortages, and patient safety within healthcare institutions. In each realm, complexity science-inspired public policy was shown to have practical and conceptually sound insights for each of the four dimensions of public policy.

For example, traditional/mechanistic approaches to HIV/AIDS public policy would include creating a national infrastructure which ensures consistency in application of policies through centralized planning in a top-down approach. Policy makers would want generalizable standards of care that focus on aggressive therapies that attack the disease and will be evaluated by randomized control trials and assesses against generalizable evidence. In contrast, a complexity science-inspired view would look for what is already working in the system to build upon existing relationships. Planning would be decentralized but within the constraints of simple rules and hence would be both top-down and bottom-up. Experiments and learning from others would be considered part of the public policy framework which is designed to work with local cultures to co-create appropriate care. There would be explicit recognition of the interdependence of the medical aspects of the disease and the social, political and economic contexts in which it manifests. Evaluation would be conducted using a balance of locally derived or highly specific evidence and evidence that is generalizable across populations or communities. A prime example of this complexity science-inspired public policy approach to HIV/AIDS is the late 1990s approach taken by Brazil which managed to stem the tide of this raging epidemic (Begun et al., 2003).

If complexity science-inspired perspectives hold such promise for health public policy, why are they not more prevalent? One of the challenges of a complexity-inspired approach is that it goes against the grain of the 'equity' value that is so central to many public policy makers and is frequently seen as synonymous with equality and hence consistency. Equality, consistency or sameness across a population is deemed to be good – is deemed to lead to equity even if the contexts in which the policy applies are radically different. Universality principles in healthcare are interpreted as consistent application of policy instruments to all. Complexity science-inspired approaches, with their emphasis on self-organization, emergence and unpredictability, fly in the face of a consistency approach. Coherence at best can be aimed for within a complexity frame. In addition, public health is almost always paid for by government which is inherently a political entity. Political agendas often call for dictated solutions from the top to show the voters that the political party in power is fulfilling their election promises. The media too plays a role in their desire for sound bites and simplistic explanations that work well as headlines. Complexity science-inspired approaches are often not conducive to a sound bite translation.

Tobacco control – Example of a complexity science-inspired approach to policy making

A prime example of the challenge of using simplistic explanations and interventions that can be explained in sound bites is the issue of tobacco control. Smoking rates are a key concern for public policy makers. Reducing the prevalence of smokers in a population results in significant increases in the health status of populations as well as reduction in healthcare costs for treatment for the diseases caused or exacerbated by smoking (e.g. lung cancer, type 2 diabetes, etc.). Yet too often the policy solutions have had limited impact (Sterman, 2006). For example, knowledge of the link between cancer and smoking, combined with a major social marketing campaign approach in most Western countries in the late twentieth century, have had considerably less than predicted impact in smoking cessation. Like the complex challenge of HIV/AIDS, smoking is deeply embedded in social and economic contexts. It is a complex public policy challenge.

The Center for Diseases Control (CDC) in the US is home to ISIS (the Initiative on the Study and Implementation of Systems). ISIS argues that complex public health challenges need to incorporate the following complexity principles:

1. *Simple rules* by which to navigate complex adaptive systems and participatory processes that engage stakeholders at all levels.
2. *Feedback* and evaluation mechanisms that allow adaptive, evolutionary change.
3. Tools and infrastructure to enable functioning as a system characterized by *connectivity* of networked interdependent stakeholders.

4 Methods for organizing and transforming knowledge which recognized *emergence* as key to achieving more effective change in the system.

They chose to study tobacco control as their initial case study to demonstrate the application of these principles.

Tobacco control involves a wide number of players including the tobacco industry, individuals, public health, media and healthcare providers. As ISIS studied the history of tobacco control strategies around the globe they identified a three stage evolution (Best et al., 2007: 227–229). In the early stages, the issue was seen as an individual behavioral change problem. Smoking cessation programs were initiated and they used individual controlled trials to study the effectiveness of various interventions for cessation and prevention of smoking. The second stage changed the unit of analysis from the individual to the population. Collaborative population-based studies using logic models were used by researchers. Broad dissemination of knowledge was seen as key and hence media and web access became increasingly significant. The third stage further extends the systems thinking to look at the person–environment interactions and networks. At this stage, both tacit and explicit knowledge are seen as important. Researchers used participatory stakeholder-based methodologies and network analyses. Complexity principles (i.e. simple rules, feedback, connectivity, and emergence) were gradually embraced explicitly or implicitly as tobacco strategy evolved.

ISIS had to confront the cultural barriers to systems thinking that dominated the tobacco field. Traditionally isolated industry players and multiple siloed disciplines in public health were linked by transdisciplinary approaches to build and maintain stakeholder relationships. Knowledge translation networks were created to support systems knowledge capacity amongst a diverse group of stakeholders. Although the ISIS project saw great progress in the global public health efforts for tobacco control, they also recommended that more needed to be done (Best et al., 2007: 233). Some were frustrated that the attempt to create systems thinking amongst all the players was not fully realized. In all, ISIS represents both the promise and practice of complexity systems thinking approaches in public policy.

COMPLEXITY AND CLINICAL MEDICINE

The clinical applications of complexity science range from technical applications, such as using fractal geometry for diagnosis and treatment of cardiac conditions, to more qualitative applications such as relationship-centered care. But the biggest impact complexity science has made in clinical medicine is in terms of a paradigm shift in the theoretical understanding of disease. Primarily this has been in the area of chronic diseases where the relevance of the reductionist paradigm has been challenged as theoretically inadequate (Petty and Petty, 2005; Brown, 2006). Reductionist modes of analysis assume that a thorough understanding of the parts will yield the greatest medical advances. Indeed, as this paradigm took hold during the twentieth century, Western medicine developed a proliferation of specialties and subspecialties. This led to a further focus on the ‘parts’ as key to understanding disease and health. General practitioners, those who by necessity looked at the connections between the parts, were not usually as well paid as specialists nor were they as highly regarded in the medical profession.

In Western societies, traditionally homeostasis, a steady state, was seen to be a sign of good health and clinical treatments were designed to return patients to this steady state. This structural reductionist approach is seen to be running out of insights for medical advancement (Petty and Petty, 2005). Complexity science, particularly the subsets of deterministic chaos and fractals, turns conventional wisdom on its ear. Rather than a steady state, a complexity science-inspired perspective posits health as more variable, more dynamic or even dynamical. And the unit of analysis shifts from an emphasis on the parts to a focus on the relationships between the parts. Focusing on biophysical dynamics can provide insights into how the connections between the system parts yield emergent behaviors which can be either functional or dysfunctional (West and Griffin, 2004). This paradigm shift has potentially enormous implications for changing the way clinicians diagnose and treat patients.

One of the areas where complexity science has made an impact in the clinical literature is in understanding the characteristics of good health in contrast with disease and dysfunction. From a complexity perspective, good health 'reflects the harmonious integration of molecules, cells, tissues and organs' and 'is dynamically stable' rather than homeostatic (Buchman, 2003). Healthy systems are said to exhibit fractal qualities such as scalar invariance, where patterns repeat across a physical or temporal space, and organized variability (Goldberger, 1997) which can be seen throughout the human body. For example, spinal motoneurons which control the movements of muscles are organized with a macro structure or organization indicating which set of motoneurons need to be firing for a specific muscle to move but need a great deal of variability to be able to adapt to the nuanced context specific movement need and also to compensate when motoneurons are injured. This state is maintained through 'feedback mechanisms and the spontaneous properties of interconnected networks' (Buchman, 2003).

In contrast, disease is characterized by a loss of variability, both within an individual and between individuals with the disease. The disease state can be conceptualized as a reordering manifestation rather than a 'disorder' which has been the long standing euphemism for disease. This reordering decreases variability, results in a loss of self-similarity and, in the long run, leads to a loss of resilience needed for health and adaptability. This 'pathological order may serve as a basis for clinical diagnosis and disease detection' (Goldberger, 1997).

In this section, we review some of the key aspects of complexity science that have impacted clinical research and practice.

Fractal geometry and clinical medicine

Clinical researchers have drawn upon the mathematical foundations of complexity science, particularly fractal geometry. Medical journals have numerous articles looking at fractal geometry in a number of clinical domains: cardiology (Bassingthwaithe et al., 1994; Goldberger, 1997; Kloner and Jennings, 2001a; 2001b; Lopez et al., 2001; Saeed, 2005), medical imaging (Chen et al., 1989), fetal development (Kikuchi et al., 2006), aging (Goldberger, 1996), comas or vegetative state (Sarà et al, 2008), neurodegenerative diseases (Scafetta et al., 2007); chronic disease (Goldberger et al., 1990), cerebral autoregulation (Latka et al., 2005), and rehabilitation (Brown, 2006). This stream of research argues that traditional medicine faces a 'central clinical paradox: individuals with a wide range of different illnesses are often characterized by strikingly periodic and predictable (ordered) dynamics, even though the disease processes themselves are referred to as dis-orders'(Goldberger, 1997: 544). The paradox is that although diseases are called dis-orders, clinicians recognize disease by its order. For example, autism and obsessive-compulsive disorders are frequently associated with highly repetitive patterns. Parkinson's disease has very little variation in the tremors and certain types of chronic leukemia show highly periodic fluctuations in neutrophil counts (Goldberger, 1997).

From a diagnostic perspective, fractal physiology points to the promise, although largely unrealized to date, of using data on the degree of variability, or orderliness, to identify a healthy or diseased state. Fractal analysis could also be used longitudinally to show the rate of change in orderliness; the faster and more profound the increase in orderliness, the more significant is the disease state or loss of good health.

Aging is a natural process of losing variability and so understanding what the typical variability is for different ages would be crucial to making sense of data on aging. Infants have far more variability in their patterns such as temperature and heart rate as do adults. This is why a baby can have a relatively high fever and still be functioning quite well whereas the same level of fever would likely represent a very dangerous state for the baby's parents and even more so for the grandparents. As we age, we lose some of our variability and hence our capacity to adapt to extremes. Hence longitudinal data would be critical to making sense of changes in variability between patients of different ages and also for a single patient over time.

Fractal patterns exhibit self-similarity or scalar invariance with irregular or jagged boundaries and, like organized variability, these are distinguishing characteristics of good health. The question becomes: what are the functions of these characteristics in good health. Do fractal patterns in space and time improve the functioning of human physiology?

If we look to fractal patterns over space, such as the vascular system, the fractal qualities allow for 'rapid and efficient transport [of blood components] over a complex, spatially distributed system' (Goldberger, 1997: 544). Fractal patterns increase the efficiency of spread throughout the system. Fractal patterns have also been observed in the healthy or efficient functioning of other organs beyond the heart, e.g. for information flow (nervous system) and absorption of nutrients (bowel).

By measuring the inter-beat intervals in hearts or breathing or even walking strides, clinical researchers have discerned fractal qualities over time in healthy patients (Scafetta et al., 2007). These fractal patterns over time allow for adaptability to changing circumstances by seemingly increasing the sensitivity of a person to subtle changes in context, particularly rapid change (Goldberger, 1996). Insensitivity to changes in context is a sign of poor health. This has been demonstrated in a number of chronic diseases (Goldberger et al., 1990). Growth restricted fetuses have a statistically reduced variability in heart beat intervals compared to normal fetuses (Kikuchi et al., 2006). Identifying the reduction of variability in various organ systems is useful in diagnosing patients (Saeed, 2005) but it is far less clear how this information could be used to treat or return patients to a healthier state. Fractal analyses could lead to treatments, both in terms of exercise and drug protocols that will increase the fractal qualities of a person's heart rate or breathing. But the science of treatment in this area is still in its infancy.

Chronic disease

Complexity science also has a lot to contribute to both diagnosis and treatment of chronic disease. Acute disease is the primary focus of most hospitals and medical school curricula. The aim when treating acute diseases is cure – to return the patient back to their normal pre-disease state. Patients are generally seen as passive recipients of treatment as they do not need to be expert in the cure to be healed. Acute diseases are usually simple or complicated in that onset is often abrupt and usually all causes can be identified and measured. However, chronic diseases are more complex. They rarely involve cure. Instead, the patient is irreversibly changed. There is often a gradual onset to chronic diseases which frequently have multi-variate causes. Diagnosis therefore becomes more uncertain and prognosis is more obscure than with single-cause acute diseases. The patient and their families need to be reciprocally knowledgeable with the healthcare professionals for any improvement in health or at least a slowdown in the evolution of the chronic disease. The aim in treating most chronic diseases is care rather than cure and the patient is a partner in the treatment rather than a passive recipient (Lorig et al., 1993; Lorig et al., 1999; Holman and Lorig, 2000).

In complexity science language, chronic diseases are unpredictable with emergent outcomes. Patients with chronic diseases, particularly the elderly, often have more than one disease and the diseases interact with each other. Reminiscent of the earlier discussion on syndemics, relationships between the afflictions are crucial. The disease and the patient co-evolve and hence the patient becomes a crucial partner in any treatment plan.

Rehabilitation medicine

Brown (2006) outlines the key characteristics of complex adaptive systems and links these to the challenges of rehabilitation medicine and, particularly, physiotherapy. He argues that the focal object or target of rehabilitation medicine is inherently a complex adaptive system with nested systems, simple iterative rules, interdependence, emergence and unpredictability. Relationships, clinical and social, are central to understanding the system and hence the key unit of analysis according to Brown. Yet the field of rehabilitation medicine has not yet adopted these ideas into their language or theories. Hence he argues many rehabilitation protocols are inconsistent with these complexity science-inspired principles and need to adopt these ideas to increase the effectiveness of rehabilitation medicine.

Examples of rehabilitation medicine failing to appreciate the complex nature of the work include the dominance of reductionist thinking which seeks single solutions for therapeutic problems. Brown (2006) argues that single solutions only work for straightforward issues (such as a ruptured appendix). Most of rehabilitation medicine deals with conditions such as rheumatoid arthritis that have co-morbidities or interdependent influences, including the medical condition itself in addition to the lifestyle and social context of the patient, all of which make it impossible to find a one-size fits all solution. Instead, rehabilitation therapists need to understand their work in terms of the relationships, the implicit attractor patterns, etc. and to create therapeutic interventions that are adaptable to the individual patient and that change over time. 'Searching for a global "best" solution is seen as a futile, counterproductive exercise in which it can take so long to formulate the action plan that the dimensions of the original problem have long since evolved and often compounded into a new issue' (Brown, 2006: 589).

The simple-complicated-complex contingency framework applied to pneumonia

In addressing the action plans for an acute illness such as pneumonia, researchers have also been struggling with the search for a global best solution. Liu et al. (2009) used the simple-complicated-complex contingency framework to identify specific improvement approaches for patients hospitalized with community acquired pneumonia. They concluded that all three categories could be applied to patients in a systematic fashion to improve the appropriate matching of medical interventions and care treatments to the nature of the problem facing the patient and the healthcare providers. By using the framework explicitly they looked to increase the success of improvement efforts and the reliability of care while retaining the much coveted physician autonomy to apply their own judgment for the more complex problems (Liu et al., 2009: 93). Healthcare improvement efforts normally require increased standardization and consistent therapeutic approaches. This increase in reliability has a cost on a cultural level because of the desire by physicians for autonomy but Stevens (2009) points out a clinical cost because the application of global standardized rules needs a more nuanced approach to deal with the context-specific needs of patients. Stevens (2009) argues that the simple-complicated-complex framework could increase the potential for physicians and other clinicians to recognize when standardization of therapies improves care and when the complexity of the context calls for a more relational approach. This relational approach implies that the patient is more involved and contextual considerations are more prominent in the choice of therapies and course of treatment than would be warranted for the known (simple) and knowable (complicated) contexts.

Relationship-centered care

Relationship-centered care is a clinical philosophy with the premise that by focusing on relational processes, care for patients can be improved. Complexity science with its focus on nonlinearity, emergence and self-organizing patterns of meaning in human interactions and patterns of relating (e.g. power relations) provides theoretical support for the relationship-centered care clinical approach (Suchman, 2006). By deliberately looking to complexity science-inspired principles, researchers and practitioners can further their depth of understanding the power of relationship-centered care (Suchman, 2006). Similarly, complexity science-inspired approaches to family nursing (Nash, 2008) aim to increase the care component of healthcare by being more deliberate in the analysis of the relationships between nurses, patients and family members. Traditional nursing theory focuses on external assessment and intervention whereas complexity science-inspired approaches move away from reductionism to a mode of inquiry and engagement that recognizes and respects nonlinearity, emergence, self-organization and uses relationship as the key unit of analysis (Gambino, 2008; Nash, 2008). This refocus of attention to things hidden from view in traditional nursing theory is most significant as we move our attention in society from a primarily acute illness needs to primarily chronic care needs (Gambino, 2008).

Although relationship-centered care began as a clinical approach, it represents the blurring of the boundaries between clinical medicine and organizational design: just as clinical practices can focus on relationships between healthcare providers and their patients for new insights into clinical interventions, organization theorists and healthcare managers can focus their attention on the relationships between organizational departments and between institutions to address the management challenges of healthcare.

Emergency medical services systems

Emergency medical services is an area that is deeply embedded in both the clinical practice domain and the management domain of healthcare. Some argue that the emergency medical services system (EMS) in the US, and elsewhere, is an obvious example of a complex adaptive system in healthcare (Trochim et al., 2006). A person calls 911 and the operator assesses the situation. Instructions to the caller are given to address basic care needs until the emergency workers (e.g. firefighters, paramedics) arrive. The emergency workers communicate with the hospital and administer care and transport. Once in the hospital the emergency department takes over and acute care needs are met or connections are made with the appropriate specialists. In the language of complexity, in the EMS independent agents following a set of simple rules interact with each other to create the system. The agents are very familiar with their own role and the simple rules they need to follow to ensure fast, effective care. Thousands of people and organizations are involved in EMS and although some agents are aware of being part of a larger system, their focus is on satisfying the local needs and connecting with adjacent parts in the system. EMS operates without a hierarchical control center; coordination is not centrally controlled and the system is highly adaptable to a wide variety of emergency medical situations (Trochim et al., 2006: 539–540).

COMPLEXITY AND THE MANAGEMENT OF HEALTH CARE ORGANIZATIONS

In the health management literature, complexity principles have been used (1) as a normative approach to create more effective healthcare delivery (Miller et al., 1998; Dershin, 1999; Anderson et al., 2000; Ashmos et al., 2000; Barger, 2003; Begun et al., 2003; Iedema et al., 2005) and to make sense of observed patterns in managing *quality* in healthcare institutions (Begun et al., 2003; Anderson et al., 2005; Stroebel et al., 2005; Chaffee and McNeill, 2007; Forbes-Thompson et al., 2007) and communities such as among Ojibwa natives (Buscell, 2006); (2) to increase *integration* in healthcare delivery by managers applying ideas such as self-organization or minimum specifications (simple rules) (Baskin et al., 2008), (3) to refocus energies in the system toward *care* and dignity for patients (Letiche, 2008).

Managing quality

Physicians, particularly primary care ones, are facing a paradox in their mode of practice. On the one hand, they are being asked to preserve their commitment to the sacredness of the doctor–patient relationship. At the same time, they are being pushed to change the way they organize and deliver care and to alter and adjust the specific skills, knowledge, and style of practice they use. Team based approaches, with teams of doctors or mixed professional teams, are considered the better approach to care and cost-containment across the Western world. Physicians are thus torn between their traditional one-to-one patient–doctor relationship and a more novel one-to-many patient–team relationship (Batalden et al., 2006). Attempts to introduce change by policy makers, administrators, and researchers have been rejected or implemented in unanticipated ways or with unforeseen consequences. Miller et al. (1998) argue that complexity science explains the organization of primary care practices and the changes needed to transform the system in a way that is more powerful than the traditional top-down, mechanistically inspired models of most healthcare policy makers and administrators. Zimmerman et al. (1998) present some prescriptive complexity science-inspired approaches for healthcare leaders and teams. In spite of its power, Miller et al. lament the limited use of complexity science in healthcare management (Miller et al., 2001).

Anderson et al. (2003, 2004) tackled the seemingly intractable problem of quality of care in nursing homes. They identified nursing homes which implicitly applied complexity principles and compared them against nursing homes with more mechanistic approaches to management and care. Their premise was that nursing homes applying complexity science-inspired approaches would fare better on key quality outcomes (aggressive behavior, restraint use, immobility of complications, and fractures) while controlling for case mix, size, ownership, and director's tenure and experience. The hypotheses were supported in that each management practice explained one or more of the resident outcomes although some of the positive results were also explained by size of the nursing home and the tenure of the director of nursing.

In a very different context, Clyde Parkis, an executive with Veteran Affairs, was charged with the task of reducing infant and maternal mortality as he led a healthcare team in Afghanistan in 2004 (Buscell, 2004). He faced a number of obstacles: the building compound had been the only hospital allowed to treat women until recently yet had also been headquarters for the Taliban, making it a hostile environment for women to visit. Other adversities included short supply in necessities and building infrastructure in disrepair. Mr Parkis realized change needed to happen at an administrative structural level to improve conditions. To do this, he applied complexity principles such as simple rules, context specificity of approaches and self-organization. His work saw positive change: infection rates had dropped from 16% to under 1% by the time he left after 2.5 months. It was too early to tell how this would impact the goals of infant and maternal mortality but there is a strong correlation between infection rates and mortality rates (Buscell, 2004).

In another example, Waterbury Hospital (Connecticut, USA) spent years working on medication management which ensures the drug routines needed by a patient before, during and after a hospital stay are appropriate and understood by patients so as to increase compliance. This may seem like a simple challenge, yet healthcare professionals are fiercely independent and patients often receive confusing or even conflicting information from the wide range of care providers involved during their stay in a hospital and after discharge. The hospital addressed the problem using a complexity science-inspired collaboration approach (termed 'positive deviance') and self-organization (Cusano, 2008).

Positive deviance is an approach that was not borne out of the complexity movement *per se* but has rather been adopted by complexity theorists who see consistency between the underlying premises and approaches of positive deviance and complexity science. The premise of positive deviance is that in every community there are certain individuals whose uncommon practices/behaviors enable them to find better solutions to problems than their neighbors who have access to the same resources (Pascale and Sternin, 2005; Walker et al., 2007). It began with the work of Jerry and Monique Sternin who demonstrated its power to reduce childhood malnutrition in Vietnam (Lapping et al., 2002; Mackintosh et al., 2002; Marsh et al., 2004); and developed its principles, many of which are consistent with complexity principles such as context-specific solutions (due to sensitive dependence on initial conditions), connectivity and relationships as the key unit of analysis, nested systems, self-organization, and simple rules.

Healthcare researchers and practitioners have begun to look at positive deviance (Smith, 1975; Tarantino, 2005) to address seemingly intractable problems such as hospital acquired infections (e.g. MRSA, C. difficile, etc.), the so called 'super bugs' because of their resistance to antibiotics. Research studies conducted in five US hospitals in 2008 and 2009 showed significant reductions in the incidence of MRSA (CBS, 2009; Medical News, 2009) which has spawned a more extensive research study still underway at the time of publication of this chapter. The Center for Disease Control is involved in positive deviance research and reports that statistically significant results are beginning to appear.[1] The positive deviance movement has generated enthusiastic support because it represents an actionable process rather than a more descriptive approach which is more common in the literature on applications of complexity science to healthcare.

Managing integration

Nursing was one of the first areas of healthcare to adopt a complexity science perspective both for clinical practices and, more significantly, for their management work. In 2008, an edited book of papers looking at nursing and complexity (Lindberg et al., 2008) outlined the role of complexity science for nursing and specifically for the role of clinical nurse leaders. The clinical nurse leader (CNL) represents the new era of nursing as a lateral integrator or connector charged with following a patient across the continuum of care in a hospital (Begun and White, 2008). The CNL view of nursing also rejects the false dichotomy or care versus science in healthcare but rather sees them as interdependent attributes (Nelson and Gordon, 2006 as cited by Begun and White, 2008). Signaling an increased role for complexity science in healthcare, clinical nurse leaders in the USA are required to study complexity theory as part of their standard curriculum for their masters' level degree. The curriculum addresses the relationships at the front-lines of healthcare, as well as complexity science-inspired management theories to address the challenging role of a clinical leader in modern hospitals and healthcare systems. Indeed, there are numerous examples of complexity science being used to transform the organization and management of healthcare services.

For example, complexity science was used as the conceptual framework for the development and formation of a Stroke Center at Saint Luke's Hospital in Kansas City (Baskin et al., 2008). Stroke victims require immediate treatment to minimize long-term damage. Hierarchical approaches in academic health centers were seen to inhibit the swift interventions needed when inpatients suffered from strokes. Because of the multidisciplinary approach to treatment, the hospital recognized a need for cooperation amongst departments and the need for a management structure different than the traditional top down model. Utilizing complexity principles of self-organization, distributed control (or shared leadership) and minimum specifications (or simple rules), a stroke center which implemented new approaches was created. These new approaches included developing a template known as 'critical path' which enabled healthcare providers throughout the system to quickly respond to stroke patients' needs and a SWAT team from the stroke center able to respond to emergencies.

Managing care

Letiche (2008) argued that healthcare management and leadership must mirror the core processes of healthcare which are inherently emergent, unpredictable, dynamic and relational. The human aspects of care are often lost in the redesign, reengineering approaches to healthcare management and hence ultimately do not have as profound an impact as their designers intended (Letiche, 2008). Complexity science-inspired approaches to healthcare, which are consistent with the core processes of care, need to be flexible, adaptable and need to deal with indeterminancy. Letiche (2008) built on Lissack and Roos' (1999) 'simple guiding principles' which are actionable, have clarity without over-specification and create conditions for accountability. The simple guiding principles require leaders to think deeply about their definitions of health, healing and wellness (Letiche, 2008) and in so doing increase the chance of bringing the humanity and care back into healthcare management. 'Healthcare leadership requires … giving definitions [of health and healing] and comparing these concretely to our possible actions' (Letiche, 2008: 16). The focus of his work is on the chronically ill for whom cure is usually not an option but rather co-created care and support are the norm. The link between the focus of clinical medicine, shifting from acute (simple or complicated) to chronic (complex) clinical challenges requires a rethinking of the management of healthcare. The interdependence of the clinical and the management or leadership aspects of healthcare is profound.

DISCUSSION: CHALLENGES COMPLEXITY SCIENCE FACES IN TRANSFORMING HEALTHCARE

Although complexity science holds out great promise for healthcare in an era of chronic disease, the promise has not been fully realized for a number of reasons. There is a lack of awareness, literacy and training for healthcare professionals in complexity science. Although there are a variety of programs in the US, UK and Canada that address this, they are a drop in the bucket compared to programs that reinforce the mechanistic, re-engineering approach to healthcare for clinicians, policy makers and managers. Indeed, the accountability and standardization trends in healthcare, although laudable for the gains they have made in outcomes, seem at odds with complexity science. Rather than seeing these as mutually exclusive options, there is a need to recognize a contingency approach so that the best of standardization can be utilized while simultaneously supporting the emergent, self-organizing and context-specific solutions suggested by a complexity science. We see glimmers of hope for the reconciliation or perhaps transcendence of the paradox but in many realms of healthcare, mechanistic approaches trump complexity science-inspired approaches for reasons of history or habit and the sophistication of the language and models of the mechanistic approach. Expediency, particularly in the politics of healthcare, often leads to quick-fix announcements to demonstrate progress on a platform agenda item. These announcements often result in decisions which are antithetical to complexity principles in that they do not take into account emergence, self-organization, relationships or context-specific solutions.

Transparency is sometimes challenging with complexity as it is hard to explain complex contexts in sound bites. Hence there may be a reversion back to the explainable – simple cause–effect relationships. Randomized control trials are seen to be the gold standard of research in healthcare. This is inconsistent with context dependent solutions and leads to suspicion of local variation. Finally, Western medical training is primarily focused on acute care, even though 70% of patients have chronic diseases. The acute care model is more consistent with the traditional mechanistic modes of healthcare clinical interventions and management. As the system of healthcare gradually reorients to focus on chronic conditions, with their unpredictable, emergent attributes and need for co-created relational care plans, the promise of complexity may yet be realized.

For healthcare researchers, complexity science offers an opportunity to study surprise, emergence and unpredictability to understand how they impact on healthcare outcomes. Deliberately focusing on relationships and patterns of interaction as the unit of analysis can lead to insights for health public policy makers, healthcare providers and managers of healthcare organizations. ISIS and the tobacco control story is an example of this shift in research focus in an applied research project focusing on public policy; the fractal movement in clinical medicine pioneered by cardiologist Ary Goldberger shows the power of using complexity to diagnose and treat a wide range of diseases; while the positive deviance movement embraces and draws upon data held by local 'experts' – those embedded deeply in the system as front-line workers and patients – to identify the simple rules that hold a system in a dysfunctional state and that need to be challenged to create positive outcomes in the management of healthcare and healthcare organizations.

Healthcare is an old industry with deeply embedded epistemologies. Dr Paul Batalden, pediatrician and prolific author in the area of quality improvement in healthcare, argues that the traditional preparation of a physician involved epistemological narrowing – dismissing all other epistemologies that are not covered in medical school curriculum.[2] Reductionist scientific approaches are legitimized at the expense of other knowledge producing modalities. Mostly ignoring sociology, anthropology, information systems, politics, economics and other epistemologies, our contemporary society has created a healthcare system with almost impenetrable barriers to shared decision making and fundamental change. Western medicine has been dominated by professions with a monopoly over both knowledge claims and service provision related to healthcare. As a result, those trained outside of traditional medical professions are frequently deemed as illegitimate interlopers. Our socially accepted modes of organizing and producing knowledge in healthcare have created a self-reinforcing closed system. Because of epistemological narrowing, particularly of physicians but more broadly across healthcare professionals, new knowledge is often not even recognized as such let alone accepted. Any study applying complexity principles will face the challenge of the narrow epistemological stance in healthcare. Between the monopolies on knowledge and service provision and the organizational silos that dominate healthcare delivery, the challenges to acceptance of complexity principles are profound. Complexity science potentially represents a fundamental challenge to the nature of expertise in healthcare. Distributed control, self-organization, emergence, unpredictability and relationship-centeredness fly in the face of traditional health care.

Yet all is not lost. Across the fields of health public policy, clinical medicine and management of healthcare organizations, there is building frustration and impatience with some of the increasingly intractable and embarrassing healthcare problems. For example, healthcare acquired infections, a topic rarely discussed a few years ago, is front page news across the globe. In many jurisdictions, policy makers are forcing healthcare institutions to reveal their statistics on how many patients were infected by their healthcare providers. The economics of healthcare are frequently one of the toughest challenges for governments (and employers) to address. There is an endless demand for expensive healthcare interventions. As boom times turn to recessions, governments can no longer afford to ignore the escalating costs of healthcare as it has been traditionally delivered. Perhaps the attention of the media and the public to such seemingly intractable problems will erode some of the impenetrable barriers to knowledge creation and a broader acceptance of complexity science in healthcare and its management.

NOTES

1 'A Successful Multi-Center Intervention to Prevent Transmission of Methicillin-resistant *Staphylococcus aureus* (MRSA)' – John Jernigan, MD and Kate Ellingson, MD presented the results of the initial research study at the Annual Society for Healthcare Epidemiology of America (SHEA) meeting, 19–22 March 2009.

2 Based on interview by author with Dr Paul Batalden, 9 April 2009.

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Author Index

Subject Index