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Complex Systems—A New Paradigm for the Integrative Study of Management, Physical, and Technological Systems

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In this introductory note, we describe the motivation for this special issue on complex systems. We begin by noting the potential management opportunities offered by recent advances in complexity science. After defining the nature of complex systems and the many ways they are expressed in organizations and markets, we briefly describe the main tools and concepts of complexity theory. We close with a brief review of the articles in this issue and their relevance to the interests and concerns of managers.

Introduction

Networks and complex systems have been the subject of a great deal of recent research. In just the last few years, hundreds of scientific papers have been written on systems as diverse as boards of directors, the World Wide Web, cells, power grids, the management and control of the transmission of infectious diseases, the efficiency of airport hubs, success of short-term project teams, and individual creativity. A growing number of popular books and articles have also tried to provide links between the basic scientific literature and the concerns of practicing managers (Barabási 2002, Strogatz 2003, Watts 2003, Ball 2004, Uzzi and Dunlap 2005). What these papers and books share is their focus on the tendency of a highly diverse set of complex systems to behave according to the principles of large scale networks (Amaral and Ottino 2004).

The broad community of scholars making advances in these areas offers a unique opportunity to promote the intellectual exchange needed to reap the benefits of this basic research for problems in management, organizations, and business. In turn, this special issue brings together original and diverse papers that use complexity theory to study the emergence, coordination, efficiency, and innovation in small groups, firms, and markets with an eye to the needs of practicing managers.

Complexity Science

Although there is no single agreed-on definition of complexity science, we believe most persons would agree that it concentrates on the study of complex systems. In contrast to simple systems, such as the pendulum, which have a small number of well-understood components, or complicated systems, such as a Boeing jet, which have many components that interact through predefined coordination rules (Perrow 1999), complex systems typical have many components that can autonomously interact through emergent rules. Gleick's (1987) national best seller *Chaos: Making A New Science*, first drew popular attention to the unique features of complex systems after the *New York Times* popularized his *butterfly effect*, which refers to the observation that a butterfly flapping its wings in India can cause a series of air movements that eventually result in a thunderstorm over Chicago. Since that time researchers have applied complexity to many social, biological, and physical systems, discovering some profound properties about complex technological-economic environments that revise, extend, and repudiate traditional strategic-planning ideas (McKelvey 2005).

In management contexts, complex systems arise whenever there are populations of interacting agents (persons, organizations, or communities) that act on their limited and local information. That is, the agents and the larger system in which they are embedded operate by trading their resources without the aid of a central control mechanism or even a clear understanding of how actions of (possibly distant) agents can affect them. As such, complex system are representative of a wide range of management problems that involve specialists who must combine their individual and deep expertise into a whole. These specialists only have limited local knowledge within an environment where rules for the planned interactions are impossible because leaders lack the necessary knowledge they need to prescribe an optimal structure or because imposing a structure would stifle individual initiative and creativity.

There are many management scenarios that exhibit network structures and emergent behavior: A design engineer may know about the reliability of individual parts but find it difficult to estimate how failures in one part of system are tied together or how errors might cascade through the system when apparently separate components have a low probability of failure (Perrow 1999, Barabási 2002). In global supply chains the notion of central management is becoming increasingly infeasible even as we become more concerned with how innovations can be disseminated or how lean supply chains can be made more robust to random errors and targeted breakdowns. At many firms, networks of constantly shifting short-term project teams may learn more effectively from informal contacts that are ostensibly outside the control of management than from official organizational documents that codify prior breakthroughs (Burt 2004, Uzzi and Spiro 2005). In world-health organizations trying to contain the spread of infectious diseases from Asia to elsewhere, there is a growing understanding that pandemics not only spread through population centers but through regional airports, which lack the conspicuousness of high volumes of travelers but which link Asia to many distant parts of the globe simultaneously (Guimera et al. 2005).

The key contribution of complexity theory to management has been to show that effective analysis and planning tools can be brought to bear on diverse organizational problems. At the core of these innovations is network analysis. Network analysis enables one to quantify the components and interactions of any type of exchange system that has actors and relationships—whether it be persons collaborating on a team, firms competing or forming alliances in a market, planes flying the same airline routes, doctors passing on new drug information in a referral network, consumers adopting the same products, or my-spacers interacting in a shared-advice network like a blog. Although network analysis has a distinguished history in social science and developed key concepts that allow one to find critical dependencies in a network, bridging actors, the most connected actors, clusters of dense relationships, the shortest path between resources, the degree of overlap or difference in communities of practice, and more; recent advances have built on an unprecedented level of cross talk among the physical, engineering, and social-science disciplines—enabling powerful ideas to come together for the first time in a novel way that is both new and relevant to strategic planning, leadership, and managerial decision making. Building on the analytical structure of agents and relationships, another breakthrough tool has been agent-based modeling. The central idea is to have agents interact with each other according to prescribed rules that may change over time as the agents adapt to their environment and learn from their experiences (Epstein and Axtell 1996, Wolfram 2002). In this way, complex interactive environments can be mapped and experimentally varied over their range to understand the possible origins of the system and how cause and effect relationships vary over the full range of key variables when there is only limited experimental data or when experimental data is expensive to generate.

Contributions in This Issue

Without any effort or direction on the part of the editors, the papers in this issue self-organized around four key cross-disciplinary themes of great current interest: evolving networks, system efficiency, cooperation, and innovation. Traditionally this section would be devoted to summarizing the separate contributions in this issue, however, as readers of *Management Science* are aware, each paper is already summarized in two styles, an academic abstract aimed at researchers, and a management insight paragraph designed to aid managers, creative artists, and other professionals in their understanding of how the basic research reported in each paper can be made relevant to practice. For this reason, we would like to draw the readers' attention to the value of having all these contributions in a single issue. Unlike what one typically finds in special issues such as this, the papers do not focus on related problems associated with a single major question. Instead, this issue offers contributions to scientific questions of management interest, such as innovation or efficiency, from remarkably different vantage points that are linked by the perspective and methods of complexity theory.

The papers by Hanaki et al., Cowan et al., and Rivkin and Siggelkow investigate how network structure affects learning through mimicry, interaction, and trial and error, and how learning, in turn, affects the network's evolution. These papers push the classic literature on the prisoner's dilemma, social dilemmas, and alliance formation—a literature primarily based in the psychology of rational actors acting independently—in a novel direction.

The contributions by Oh and Jeon, Iravani et al., and Braha and Bar-Yam describe and model how an understanding of variation in network structure influences the efficiency, resource allocation, and robustness of decentralized systems, such as online communities and distributed work teams. This is a new and expanding area of research that addresses the question of how efficiency and resource allocation can be achieved without a master planner, designated coordinator, or prices.

Finally, Linn and Tay, Huang et al., Schilling and Phelps, and Kogut et al. address different aspects of the uncertainty/innovation problem in markets and industries. Contributing in novel ways to the large literature on individual decision making, uncertainty, and innovation, they investigate how the macro network structure, within which individuals or collective actors are embedded, conditions the behavior of the agents and the returns they garner in different types of markets.

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