Introduction to the Special Issue: Applications of Complexity Theory to Organization Science

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In crafting the call for papers for this special issue of *Organization Science,* the appointed editors wrote:

> Organizational scholars seldom come to grips with nonlinear phenomena. Instead, we tend to model phenomena as if they were linear in order to make them tractable, and we tend to model aggregate behavior as if it is produced by individual entities which all exhibit average behavior . . . a different view of complexity is emerging that may have important implications for organizational scholarship. Within the past decade, interest in the "sciences of complexity" has increased dramatically. The study of complex system dynamics has perhaps progressed furthest in the natural sciences, but it is also beginning to penetrate the social sciences. This interdisciplinary field of study is still pre-paradigmatic, and it embraces a wide variety of approaches. Although it is not yet clear whether a genuine science of complexity will emerge, it does seem clear that scholars in a variety of fields are viewing complexity in a different way than organizational scholars traditionally have. At this juncture, organizational researchers have few templates that suggest to them how to hypothesize about or model such behavior. It is difficult to know how to draw a conceptual model and how to report the results of empirical inquiries into complex organizational phenomena. The special issue aims to provide scholars with useful templates to follow when analyzing complex processes that involve organizations.

The seven articles that appear in this special issue concerning applications of complexity theory to organizations push our field forward significantly, not simply by importing ideas from an emerging interdisciplinary area, but by using them to inform rich, theoretically-grounded depictions of how organizations operate. Each emphasizes how the interaction of elements in a system produces surprising, emergent behavior that can be understood through formal models, even if those models cannot necessarily predict how a given system will evolve. Together, they constitute a foundation for a new way of thinking about how to model nonlinear behavior in organizations.

Dooley and Van de Ven's article establishes a framework for deciding which kind of process theory is best suited for explaining the dynamics of a particular empirical time series. These authors describe four types of time series, distinguishing periodic and chaotic dynamics from colored noise and genuine randomness ("white noise"). Using this classification scheme helps organizational researchers decide what type of model and what type of analytical approach to take when assessing empirical time series data.

Dooley and Van de Ven lucidly describe what chaos is and how it differs from "pink noise," time series generated by systems whose behavior is distributed according to power laws. Which causal theory a researcher adopts to describe the outcome of a process that unfolds over time depends on how many different independent variables he believes are influencing a system's output, and how tightly or loosely these variables interact with one another. Through an illustration of how sequence data from an innovation study might appear in different forms, they provide a clear procedure for diagnosing what type of causal model would be most appropriate, noting that for many time series, multiple process theories may be required to generate an adequate explanation.

Once a scholar has concluded that a particular time series exhibits pink noise, he or she must decide how to

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model the underlying process. Kauffman (1993) introduced an influential model based on Boolean networks, which consist of nodes that turn on or off depending on the state of other nodes to which they are connected. The most interesting properties of the model depend on two parameters: *n,* the number of elements in the network, and *k,* the number of elements that a node accepts as inputs. Consequently, Kauffman's approach is often termed "the *NK* model." Three papers in this special issue build on this way of modeling complex adaptive systems.

McKelvey delves deeply into the seldom-examined details of Kauffman's studies, and identifies a number of ambiguities and difficulties. He concludes that before organizational scholars adopt the *NK* model, they should modify Kauffman's operationalization of it. McKelvey does not advocate abandoning the *NK* approach; on the contrary, he contends that Kauffman's theory has rich implications for organizational research, if it is properly operationalized.

The thrust of McKelvey's criticism, which applies to any model of complex systems, is that appropriate CAS models embrace heterogeneity among agents and their inputs, instead of trying to average them away. McKelvey is particularly critical of approaches that depict the total fitness of a system as the average of its components' fitness. He argues that if one focuses instead on the performance of the weakest link in a network, the results of *NK* simulations change significantly. He also criticizes Kauffman's decision to model his Boolean network as if every node had exactly the same number (*k*) of inputs. McKelvey suggests that if the number of inputs is allowed to vary around an average, fitness landscapes will display much more variation, creating more interesting opportunities for evolution. McKelvey's cogent analysis of the *NK* model should be required reading for scholars interested in this particular approach, but it also highlights for scholars employing different perspectives the importance of focusing on individual behavior instead of average behavior when analyzing complex systems.

Boisot and Child's paper views organizations as interpretive systems that first create, then objectify the world through structuration (Giddens, 1974). Because organizations are loosely coupled systems with many combinatorial possibilities, their members must make sense of them either by reducing their complexity (lowering the number of agents whose inputs influence their behavior) or by absorbing it (adopting cognitive structures that simplify the inputs). The way organizational members process complex inputs is visualized as an "I-Space," a three-dimensional space in which information is more or less codified and more or less abstracted into an objectified structure, and an interpretation is more or less widely diffused among organizational members. Four types of organizational forms—fiefs, clans, bureaucracies, and markets—can be located at different positions in this I-Space.

Building on Kauffman's *NK* model, Boisot and Child suggest that the I-Space contains a chaotic regime and an ordered regime. In between lies the poised state between order and chaos. There is no one combination of codification, abstraction, and diffusion that produces the best performance; the four types of organizations are different responses to the challenge of living between too much order and too much disorder.

Boisot and Child describe the point in the I-Space that Chinese organizations appear to have evolved toward, one with few stable rules and many differentiated subsystems, with few, loose ties between components, but many rich ties within each one. The Chinese have historically preferred to absorb complexity by absorbing it (through dense interpersonal linkages within tightly bounded communities) instead of reducing it via codification and abstraction. In contrast, Western firms have preferred to reduce complexity through rule systems and legal institutions. Consequently, Western multinationals operating in China must make a crucial strategic choice: they can try to cope with a complex environment by reducing complexity through importing standard policies and procedures, or they can try to absorb it by building a relational network of allies. Which strategy is to be preferred depends on a variety of factors, creating an agenda for future research.

Levinthal and Warglien employ the *NK* model to bring a new perspective to organization design. Traditionally, organization designers have taken task interdependencies as a given, and have focused on maximizing the intensity of interactions within an organization unit and minimizing interactions between them. Levinthal and Warglien propose "landscape design," influencing a self-organizing system by manipulating the interdependencies between policies or actors.

In situations where there is one best approach, they suggest, the payoffs to an actor should be independent of what other actors do. Absent interdependence, adaptive landscapes will have a single peak, and agents who behave rationally will locate it. On the other hand, when there is not a single optimum, one may wish to encourage search behavior. This can be accomplished by making actors more interdependent with one another in search of a common goal—for example, by forming them into cross-functional teams or requiring tighter synchronization among their actions. This will encourage them to recombine partial solutions, bringing together elements that were previously known but distant from one another.

The most challenging situations to manage are those where each actor's payoffs depend not only on which k actors he or she is interdependent with, but also on some number c of choices or attributes they display. In these landscapes, which are encountered in team production problems, for instance, the design challenge is to encourage cooperation given the emergence of social dilemmas. Levinthal and Warglien articulate a variety of mechanisms for igniting cooperation, which will reinforce itself if only landscape designers can get it started.

Each of the remaining three papers in this special issue introduces a novel way of modeling complex systems. Morel and Ramanujam draw upon graph theory and Frank and Fahrbach adapt social network models by turning them into dynamical systems, while Sterman and Wittenberg simulate an ecology of interacting schemata.

Morel and Ramanujam set out to disentangle a set of concepts that are often confounded in unsophisticated discussions of complexity theory, cautioning that the kind of self-organization that is relevant for organization theory is not the same as that encountered in biology or computer science. They argue that organization theorists should consider models in which the external pressure of competition drives internal organizational changes, and they present a model that views organizations as a connected set of routines. In Morel and Ramanujam's model, the routine with the poorest performance is reengineered, causing both its performance and that of all routines connected to it to change. The result is a punctuated equilibrium that displays a power-law relationship between the frequency and magnitude of change. Morel and Ramanujam carefully distinguish this outcome from dynamical self-organization—a progressive shift in the fitness distribution toward higher and higher levels—and biological self-organization—the emergence of chemical reactions that catalyze themselves, leading ultimately to the creation of life. Their analysis sheds a clear light on what it means to say that complex systems self-organize and brings needed rigor to discussions of what it means to say that organizations evolve toward a dynamic equilibrium at the edge of chaos.

Frank and Fahrbach's paper extends social network analysis, pointing the way toward dynamic models of how ties evolve over time. They point out that the underlying basis of organizations is both the structure of interaction among member and the distribution of sentiments among them. Changing interaction patterns can change the distribution of ideas and attitudes, which in turn can alter the ties among actors. Frank and Fahrbach note that most models have treated one as the outcome of the other, and thus have not integrated the two in a dynamical system of feedback loops.

These authors develop a new model in which the sentiments of an actor at time t depend on the sentiments of others to whom he is connected at time $t - 1$. The degree to which an actor's sentiments are sensitive to the opinions of others is treated as a variable. In an initial simple model, actors almost always more toward agreement, but positive feedback loops mean their shared opinions become more and more extreme without limit. Solutions to this problem have typically relied on mathematical restrictions that Frank and Fahrbach reject as unrealistic. Instead, they argue that actors not only want to connect with others who share their sentiments, but also actively seek out new information. Introducing this tendency into the original model dampens its explosive tendencies. Elaborating the model still further, by allowing actors to seek out new connections as well as new ideas, generates a full range of complex behavior.

Frank and Fahrbach's paper highlights the importance of modeling simultaneously the schemata of agents in a complex system and the pattern of ties that connect agents. Their analysis also demonstrates how a variety of structural models can be turned into dynamical systems, in which the state of an actor at time t influences its state at $t + 1$. Frank and Fahrbach not only show how complex behavior can be generated from a simple system of differential equations, they also provide a framework within which novel hypotheses can be generated and tested with actual data.

Sterman and Wittenberg's paper demonstrates how organizational scholars can model the evolution of actors' schemata over time. They model the onset of scientific revolutions by creating a simulated ecology of interacting, competing paradigms. This simulation draws extensively from the heritage of systems dynamics models, but the variables in the model depend on the number and state of other schemata in the system (in this case, scientific paradigms) at the random moment when a new schema appears.

By including positive feedback loops in their model, Sterman and Wittenberg generate the sensitivity to initial conditions that characterizes systems in chaotic equilibria. Paradigms that are initially quite similar experience very divergent fates, because positive feedback magnifies the small differences between them. Which paradigm survives and grows to dominance depends on the specific historical conditions that prevail at its birth.

Sterman and Wittenberg demonstrate how statistical hypothesis tests can be conducted using bootstrapped estimates from many iterations of their model. Although their model does not use actual empirical data, their approach demonstrates how one can generate and test falsifiable propositions, given a range of data points. They elegantly show how altering conditions one at a time in a simulation creates opportunities to develop grounded theory without simplifying away the rich interaction that leads to complex behavior in a system.

In summary, this special issue introduces to organizational scholars a way of diagnosing whether a system exhibits chaotic or complex behavior, and a variety of different models for analyzing the nonlinear dynamics of complex systems. These papers draw on a wide variety of intellectual antecedents—ranging from classical organization design to interpretive theory to social network analysis to evolutionary epistemology—demonstrating that complexity theory is a rich perspective for viewing many different aspects of organizations. The purpose of this special issue was to generate a critical mass of papers that could significantly shorten the time it will take models of complex systems to diffuse and become commonplace in journals devoted to the study of organizations. We believe these seven papers serve as a springboard for future research, by providing a rich set of exemplars on which scholars with many different interests and backgrounds can build.