The Matrix of Complexity: A Multi-Disciplinary Approach for Studying Emergence in Coevolution •

Benyamin Bergmann Lichtenstein

Department of Management and Marketing
University of Hartford
West Hartford, CT 06117-1599
860/768-4270
<Benyamin@mail.hartford.edu>

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NOTE TO COLLEAGUES!!

My goal is to extend this paper, generalize it to Organization Theory (rather than focus on co-evolution), and submit it to Academy of Management Review. However, I NEED YOUR HELP! What should a 'review' and theoretical contribution on Complexity Research look like? What should it include, and how should the field be represented at this early stage in its development? Please give me whatever suggestions you like - particularly around my choice of disciplines in Table 1, and let me know if you would consider a form of co-authorship. THANK YOU!!

INTRODUCTION

Many researchers have been suggesting that complexity research can play an important role in organization science (Brown & Eisenhardt, 1997; Anderson, 1999a; McKelvey, 1999a).[2] For example, in the past few years scholars have used a variety of dynamic systems theories to provide a more complete understanding of organization design (Levinthal and Warglien, 1999), network structuring (Carley, 1999) and strategic adaptation (McKelvey, 1999b). In addition, the concepts of emergence and self-organization have been used to explain various elements of strategic decision making (Bettis and Prahalad, 1995; Stacey, 1995; MacIntosh and MacLean, 1999), entrepreneurship (Stevenson and Harmeling, 1990; Gartner, 1993), career theory (Bird, 1998), organizational learning (Nonaka, 1988; 1994), leadership (Senge, 1990b; McKelvey, 2000), and organizational change and transformation (Leifer, 1989; Dooley, 1997).

More recently, scholars have recognized the potential role of complexity research in explaining coevolutionary properties and processes (Baum, 1999; Lewin, Long and Carroll, 1999; Lewin and Volberda, 1999; McKelvey, 1999). Complexity models and methods may be particularly valuable for studying the multi-level properties, multi-directional causalities, non-linearities, positive feedbacks, and path dependent processes that are at the heart of coevolutionary research (Lewin and Voldberda, 1999). Additionally, complexity research provides an excellent framework for understanding adaptive ordering in dynamic environments, one of the central issues in coevolutionary research (Lewin and Voldberda, 1999; Lewin et al., 1999). These possibilities, like those identified in uni-disciplinary studies mentioned above (e.g. organization design, strategy, entrepreneurship), have generated a great deal of enthusiasm for the long-term prospects of applying complexity theory to management (McKelvey, 1999a).

As one might expect (Abrahamson, 1996), this enthusiasm has sparked a proliferation of popular managerial articles and books that utilize complexity models to explain everything from strategy formation (Stacy, 1992; Beinhocker, 1999) to management practice (Wheatley and Kellner-Rogers, 1996; Lissack and Roos, 1999); from product development (Brown and Eisenhardt, 1998) to organizational development (Goldstein, 1994). This diversity in topic and method is matched by differing expectations about how complexity should be understood. Some authors think of complexity as a science (Dent, 1999), others see it as a theory (Anderson, 1999a), and others consider it "collection of results, models, and methods" (Cohen, 1999: 375). Some place its origin in the research leading to the Santa Fe Institute (Waldrop, 1992), others mark its beginnings in the mathematics of deterministic chaos (Gleick, 1987), while others locate its source in cybernetics and dynamic systems modeling (Capra, 1996).

What is the essence of this diverse stream of writing and research? Is there a way to organize the multiple approaches into a coherent framework? Why is such a broad range of

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[2] The historical nature of our argument is reflected throughout the paper, thus all references are organized

writing being labeled as “complexity”? In this brief review article I will offer a context for answering these questions. I start by suggesting that “emergence” is the core issue that integrates the majority of research being placed under the complexity banner. Next I outline a typology (“the matrix”) for distinguishing between 13 complexity approaches. Then I show how each of these approaches can support the development and testing of coevolutionary theory. Finally I argue that the more self-conscious we can be about the nature of complexity research, the more likely it is that complexity will emerge as a cogent paradigm rather than a passing fad (McKelvey, 1999a).

THE SCIENCE OF EMERGENCE

Brief History and A Definition of Complexity Research

Research underlying what is being called “complexity” has existed for many decades. Its origins, according to some complexity scholars (McKelvey, 1999a), are in Prigogine’s research on “dissipative structures,” which explains how regimes of order come into being and retain their form amidst a constant dissipation of energy and resources (Prigogine, 1955). This idea became popularized in the 1960s and 1970s as general systems theory (von Bertalanffy, 1968; Miller, 1978) and open systems (Kast and Rosenzweig, 1972), whose applications were foundational to organization science (Lawrence and Lorsch, 1967; Thompson, 1967; cf. Ashmos and Huber, 1987).

During this same period researchers in a wide variety of fields were experimenting with non-linear models of dynamic systems. Several major schools of thought were born of these explorations, including cybernetics (Weiner, 1948/1961), system dynamics (Forrester, 1961; Maruyama, 1963), computational genetic algorithms (Neumann, 1966), dissipative

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by date order rather than alphabetically. References in the same year are listed alphabetically.

self-organization (Prigogine and Glansdorff, 1971), complex adaptive systems (Holland, 1975), deterministic chaos theory (May, 1976), catastrophe theory (Zeeman, 1977), synergetics (Haken, 1977), autopoiesis (Maturana and Varela, 1980), and fractals (Mandelbrot, 1983). With Gleick's (1987) best-selling book many of these approaches became known as "chaos" theories. Some years later Lewin (1992) and Waldrop (1992) developed syntheses of these models using "complexity" as an overarching framework. These insights have been applied to management in new journals such as Emergence (Lissack, 1999) and Nonlinear Dynamics, Psychology, and Life Sciences (Dooley, 1997) and have been featured in several special issues, including the Journal of Management Inquiry (Bartunek, 1994), Organization Science (Anderson, Meyer, Eisenhardt, Carley and Pettigrew, 1999), and the Journal of Business and Entrepreneurship (Black, 1999).

Each complexity theorist tends to specialize in one or two disciplinary methods for studying complex dynamical systems; one goal of this article is to connect and begin to integrate these various approaches. An overview of the breadth of these disciplinary approaches is presented in Table 1. The table is based on overviews and summary accounts by Gleick (1987), Lewin (1992), Waldrop (1992), Casti (1994), Cowan, Pines & Meltzer (1994), Goerner (1994), Guastello (1995), Capra (1996), Elliott & Kiel (1996), Dooley (1997), Eve, Horsfall & Lee (1997), Anderson, et al., (1999); Goldstein (1999), Marion (1999), and McKelvey (1999a, 1999b). Undoubtedly some scholars will disagree with the categorizations and brief descriptions of these disciplinary approaches; this list should properly be thought of as an evolving framework (a complex adaptive system) that will change based on feedback from readers like yourself.[3] Nevertheless, this table does provide a starting point for bounding complexity research.

Please See Table 1--*Place about here*

The goal of this paper is not to provide yet another introduction to each of the disciplines—the summaries that were used to develop Exhibit 1 do an excellent job of accomplishing this task. Instead, our goal is to answer the question: What is the essence of complexity research? What are complexity researchers trying to understand in the context of management and organization theory?

In my view, each of these 13 disciplines of complexity explores the conditions, properties, or processes of emergence in dynamic, complex systems. At its essence, complexity researchers are providing new ways to understand how and why order emerges. Formally, emergence means the creation of coherent structures in a dynamic system (Bushev, 1994; Holland, 1994). Most often emergence is designated as the process by which "…patterns or global-level structures arise from interactive local-level processes. …[The] combination of elements with one another brings with it something that was not there before" (Mead, 1932: 641; in Mihata, 1997: 31).

The study of emergence has been a prominent topic in many fields, including philosophy (Pepper, 1926; Bedau, 1997; Goldstein, 2000), social psychology (Allport, 1962), sociology (Buckley, 1967; Eve, Horsfall and Lee, 1997), and organization science (Dansereau, Yammarino and Kohles, 1999). Complexity researchers have argued that the confluence of mathematical tools and computing techniques allow for an in-depth and

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[3] Please participate in the evolution of this list by e-mailing your comments to Benyamin@mail.hartford.edu.

rigorous exploration of emergence across a wide spectrum of system levels (Waldrop, 1992; Cowan, Pines and Meltzer, 1994). How can this matrix of levels and approaches be understood?

A Typology of Approaches for Studying Emergence

Each of the complexity disciplines listed in Table 1 explores emergence in a different way. Thus, moving from a loose collection of metaphors to a rigorous scientific enterprise (McKelvey, 1999a) requires a more in depth analysis. A useful beginning would be to differentiate the disciplines according to their type of analysis (Crutchfield, 1994), and their epistemic approach (McKelvey, 1999c). With these two dimensions a typology of emergence disciplines is generated in Table 2, which can help management scholars find the appropriate method for theory building and empirical testing.

The first dimension is presented by Crutchfield (1994), who distinguishes complexity theories according to their different types of analysis—discovery, modeling, and intrinsic emergence—referring to the aspect or quality of emergence each theory seeks to explain. The first type refers to the *discovery* that something new has appeared in a complex system. Fractal analysis or deterministic chaos theory fits into this category, the latter of which has been used to *discover* order in apparently random time series. Chaos theory has been used to identify periods of nonlinear interaction across a set of common factors in the early stages of two innovation ventures (Cheng and Van de Ven, 1996), and the distributions of work behavior in public service organizations (Kiel, 1994). Separately, through the mathematics of self-organized criticality, significant regularities have been found in the size/structure relationships across tens of thousands of businesses in the U.S. (Stanley et al., 1996). The discovery of order at this level is in the eye of an observer: “Surely, the system state doesn’t know its behavior is unpredictable" (Crutchfield, 1994: 517). Thus, theories at this level usually involve post-hoc analysis of time series that are "objectively" separate from the researcher.

The second type refers to the *modeling* of emergence, in which computational or mathematical systems are developed to represent system emergence. This level refers to research streams that have deduced rules or heuristics from simple systems and used them to develop modeling contexts in which order emerges over time. For example, Kauffman's (1993) "NK landscapes" have been used to model the order that can emerge in co-evolutionary niches (Baum, 1999). Using different computational methods, system dynamics has been used to model the unexpected outcomes of strategic decisions in complex systems (Hall, 1976) and of theoretical assumptions in complex theories (Sastry, 1997). Other examples of this level include self-organized criticality, which has been used to model the behavior of stock markets (Bak, 1996), and catastrophe theory, which has been used to model discontinuities in organizational behavior (Guastello, 1995), strategic change (Gresov, Haveman and Oliva, 1993) and organizational transformation (Bigelow, 1982; Brown, 1995). In this context, theorists are more involved in the emergence process, as they identify rules and mathematical relationships that are used to computationally recreate emergent processes in complex systems.

Crutchfield's final type is *"intrinsic emergence,"* in which the increased capabilities generated by the system's emergence can be capitalized on by the system itself, lending additional functionality to the system (1994: 518). In a sense, rather than a description of or model about emergence, in intrinsic emergence the "observer" is a part of the system, and thus "has the requisite information processing capability with which to take advantage of the emergent patterns." Behavioral descriptions of "dissipative structures" (Leifer, 1989; Smith and Gemmill, 1991) and organizations "at the edge of chaos" (Dubinskas, 1994; Brown and Eisenhardt, 1997) fall into this category. To the degree that an agent within a complex adaptive system [CAS] can extend its behavioral capabilities by learning over time (Gell-Mann, 1994), studies on the evolution of CAS also fall into this category (Holland, 1995; Macready and Meyer, 1999). Within this type of analysis, the process of emergence presents insights that influence the development of the theories and to some extent of the theorists themselves (Wilber, 1998; Lichtenstein, 2000a).

Please See Table 2--*Place about here*

The second dimension distinguishing these theories is based on the quasi-realist epistemology that McKelvey argues is a basis for complexity science research (McKelvey, 1997; 1999c). His philosophical study is aimed at generating an epistemology for organization scientists that recognizes the socially constructed meaning of terms without lapsing into a form of relativism that eschews progress in understanding social systems. The result is a "model-centered epistemology in which [organization] science is divided into two independent activities" (McKelvey, 1999c: 289); one is a validation of the link between abstract theory and formal model, the other validates the link between the model and the phenomenal world. McKelvey's distinction is depicted in Figure 1.

Please See Figure 1--*Place about here*

The first of these activities involves the coevolution of a theory and its formal model which is an idealized—computational or laboratory—representation of the theory (Carley, 1995). In this view, theoretical adequacy is gained to the extent that the theory can explain model behavior. This activity is exemplified by the advances in NK models to represent the theory of co-evolution (e.g. Baum, 1999; McKelvey, 1999b; Lewin, et al., 1999). Another example is the use of simulated annealing to model the process of organizational design an adaptation (Carley and Svoboda, 1996; Carley, 1998).

Secondly, parallel to confirming the computational adequacy of the theory-model relationship, is generating trustworthiness and credibility in the relationship between model and organizational reality, i.e. how well the model represents the real-world phenomena within the scope of the theory (McKelvey, 1999a: 18). Here again, the model-phenomena link is co-evolutionarily developed, leading to improvements in the model and at the same time, better explanations of real-world behavior (McKelvey, 1999c: 289). Examples of this activity include the use of dissipative structures models to explain organizational behavior (Ulrich and Probst, 1984), strategic change (MacIntosh and MacLean, 1999), and entrepreneurial development (Lichtenstein, in press), the use of system dynamics to explain complex organizational failures (Hall, 1976), and the use of autogenesis to explain the nature of organizing in dynamic and bureaucratic situations (Drazin and Van de Ven, 1985; Kickert, 1993). Additionally, NK models are being utilized to better explain the competitive dynamics in particular industries (Sorenson, 1997).

Although some approaches can be used for both purposes, in general the theories of complexity can be distinguished by which of the two activities they excel in. Some focus on a computational approach to develop models that represent theory, others operationalize these models in empirical studies that test the reliability and validity of the model in real-world situation. At the same time, as we saw above, some disciplinary approaches have been applied in both ways—generating models from theory, and testing them using phenomenological data. Likewise, a single approach could well be used in more than one type of analysis in Crutchfiled's sense. Thus, the matrix is much more complex than I am making it out to be; yet it provides a basic framework that can help scholars distinguish multiple frames of reference.

Key Assumptions of Complexity Theory

As a whole these disciplines offer a new basis from which to understand the nature of organizing and management. According to some, this shift is so fundamental that it requires an entirely new science for studying organizations (Overman, 1996). A good example is given by Stevenson and Harmeling (1990: 3), who describe this new management science as one in which:

> ...the most critical knowledge in our real world is not what "is," but how various elements of the universe relate and interact....[O]nly a brave new management science could begin to bridge the great gulf between how things are done now and how they should be done in the face of a rapidly changing future.

At the core of such a new science is a reframing of assumptions, which generate a new "mental model" for researchers and practitioners of management. For example, Dent (1999) suggests numerous differences between traditional management theory and an emerging world view, including shifts from a focus on discrete entities to a focus on relationships between entities (Bradbury and Lichtenstein, 2000), from language as representation to language as action (Gergen and Thatchenkery, 1996), and from a solely selectionist approach to one that sees adaptive self-organization as a complementary process to selection/retention in evolutionary development (White, Marin, Brazeal and Friedman, 1997; Lewin and Voldberda, 1999).

Perhaps the single most important of these shifts is a movement away from explaining why *change* happens and toward explaining why and how *order emerges* in the first place (Stevenson & Harmeling, 1990). The need for making this shift can be traced to an inaccurate definition embedded in original descriptions of open systems theories by organization theorists (Lewin, 1936; Katz and Kahn, 1966; Thompson, 1967). Traditionally, organizations (all social systems) have been seen as essentially stable entities, i.e. they exist in a state of "equilibrium." However, this perception is based on the definition of equilibrium taken from mechanical engineering and physics, which define equilibrium as the point of greatest stability, the state in which a system has the greatest likelihood of retaining its internal order (Bettis & Prahalad, 1995). The goal of management, therefore, is to maximize an organization's "fit" with its environment (Drazin and Van de Ven, 1985) in various ways (e.g. Lewin, 1936; Thompson, 1967.)

Unfortunately, this definition of equilibrium has been confused with the definition of equilibrium used by thermodynamics, the science from which open systems theory was developed (Prigogine and Stengers, 1984). In thermodynamic terms a system at equilibrium contains absolutely no order whatsoever. Thus by definition neither natural nor social systems can exist at thermodynamic equilibrium (Salthe, 1989; MacIntosh and MacLean, 1999). Instead, all organized entities are understood as dynamic structuring processes continuously creating and re-creating internal order by maximizing the acquisition and dissipation of resources (Schrodinger, 1944/1992; Nicolis, 1989; Drazin and Sandelands, 1992).

Why is this distinction important? In the mechanistic paradigm systems are assumed to be stable, thus the question of organization theory is: "why and how do organizations and their structures change?" (e.g. Van de Ven and Poole, 1995). In contrast, the new paradigm is based on the assumption that change is the norm, so the key question of organization science is reversed: "Why does order emerge, and how does it maintain its existence over time?" Each of the complexity disciplines provides a different lens to explore that question, by focusing on a specific quality of emergence. These questions are particularly relevant in the study of coevolution, which is aimed at understanding the emergence of coherent, system-wide behaviors at multiple levels of analysis (Whittington, Pettigrew, Peck, Fenton and Conyon, 1999). In the following section, I provide some initial suggestions for how complexity disciplines can inform and extend current research on coevolution.

COMPLEXITY THEORIES IN COEVOLUTION RESEARCH

Advances in complexity science may help provide "a much needed theoretical footing for coevolutionary research" (Lewin and Volberda, 1999: 528). Many of the key processes in coevolution—adaptation on multiple levels, dynamic feedback loops, mutually causal flows of knowledge across boundaries—are at the core of several complexity disciplines. More importantly, the essential goal of coevolution—studying the adaptive changes within and between all levels of organizational and environmental interactions—can be operationalized in terms of emergence, the coming-into-being of "macropatterns that depend on [continuously] shifting micropatterns" (Holland, 1998: 7). These potential contributions can be drawn out through a review of Lewin, Long and Carroll's (1999) "theory of coevolution," with additional context from Lewin and Volberda's (1999) properties and requirements for coevolutionary research.

In these coevolution models, firms seek a balance between exploitation and exploration efforts over time, in order to remain competitive in changing environmental circumstances (Lewin et al., 1999). These ongoing efforts are reflected in a firm's legacy, which encompasses firm level knowledge, capital, technological platforms, capabilities, as well as characteristics of the industry. In this sense a firm's legacy can be modeled as a complex attractor (Marion, 1999), which, like strange attractors in *deterministic chaos* *theory*, provides a method for mapping the dynamics of interactive systems. This approach is particularly useful for identifying the path dependency and historical embeddedness of firms, key properties of coevolution (Lewin and Volberda, 1999).

According to this view, exploitation and exploration processes are complementary means for optimizing organizational resources and design features in the face of multiple environmental and path dependent constraints. *Simulated annealing* is a powerful method for modeling this optimization process of strategic adaptation and change (Carley, 1998). Simulated annealing is a theory-building tool that models solutions for a particular class of design problems, "the need to locate the organizational design that optimizes organizational performance subject to various constraints" (Carley, 1998: 29). By stripping the problem to its core elements, it provides a framework for theorizing how organizations optimize adaptive behaviors (Carley and Svoboda, 1996); the multi-level nature of the framework may be especially useful for coevolutionary research.

Studying change at multiple levels simultaneously is at the heart of coevolution research: "The theory assumes that organizations, industries and environments co-evolve" in a multi-directional way (Lewin, et al., 1999: 536). This process of organization-environment coevolution can be modeled as an *NK landscape* (Kauffman, 1993; McKelvey, 1999b). In this class of models, competitive characteristics of adaptive entities (organizations, for example) are reflected in a topological landscape that defines the relative fitness contribution of each of those characteristics. By including an additional parameter, the "NKC" model shows how changes in organizational fitness levels result in changes to the landscape itself. Researchers have used this multi-level interactive approach to explore the coevolution of capabilities and industries (Levinthal and Myatt, 1994), scientific invention and technological innovation (Fleming and Sorenson, 2001) and inter-firm value chain networks (McKelvey, 1999b). This complexity discipline thus offers a precise way to operationalize the multilevel embeddedness of coevolution.

Complex adaptive systems offers an alternative approach for studying the emergent behaviors of agents or populations adapting and coevolving in a computational context (Holland, 1998). In complex adaptive systems, “agents adapt by changing their rules as experience accumulates” (Holland, 1995: 10). In addition, “each change of strategy by a worker alters the context in which the next change will be tried and evaluated. When multiple populations of agents are adapting to each other, the result is a coevolutionary process” (Axelrod and Cohen, 2000: 8). Studying this emergence process can generate insights about the “mutual, simultaneous, lagged, and nested effects” of coevolution (Lewin and Volberda, 1999). Perhaps more important, CAS as a discipline can help define interaction process that hold across levels, which may allow researchers to identify similar patterns acting in macroevolution and in microevolution (Axelrod and Cohen, 2000)

This search for similar patterns across scale can be aided by the mathematics of *fractals* (Mandelbrot, 1983). The fractal notion of “self-similarity across scales,” and the resulting topological mapping techniques used to uncover those often unseen patterns, has been under-utilized by complexity scholars (Zimmerman and Hurst, 1990). Although the operationalization of “fractal dimensions” may not yet be obvious in coevolutionary contexts, the mathematics is a unique way to reveal whole-part relations that are a key to understanding mutual adaptation processes.

A critical part of explaining interactions between and across levels is the feedback loops that are involved. “The goal of coevolutionary inquiry is understanding how the structure of direct interactions and feedback within organization-environment systems give rise to their dynamic behavior” (Baum and Singh, 1994: 380). These bi-directional influencing processes are a central property of coevolution research, and *system dynamics* provides a powerful means for modeling the non-linearities of these positive feedback systems (Sastry, 1997). System dynamics forces researchers to carefully identify each feedback process within an entire system; the rule-based computational model can reveal hidden interdependencies and emergent characteristics that are not tractable using linear thinking (Hall, 1976).

At a more micro level, *cellular automata* modeling could augment coevolution research by examining the relationship between individual agent moves (e.g. strategic adaptations) and the moves of that agent's immediate neighbors (Krugman, 1996). For example, the competitive dynamics of an industry can be modeled as rules that are followed by an organization's direct competitors, allowing for an examination of how firm-level decisions are affected by others in its physical or competitive location. Like other computation-based disciplines of complexity, the algorithmic tractability of the model makes it easy to test many different configurations in a short period of time, thus speeding up the theory-building process (Axelrod, 1984; Carley, 1996; Holland, 1998).

Whereas many of these computational models are grounded in structured rules that mediate flows of behavior, deep structures and resource flows are also at the heart of the qualitative theories of *autogenesis/autopoiesis.* Autogenesis is a theory of identity-making, in which an agent's core values and schemas define the rules that formulate emergent structures (Drazin and Sandelands, 1992). The value of autogenesis/autopoiesis is its conceptualization of the mutual causality of resource flows and environmental potentials (Swenson, 1992; Swenson, 1997). According to the theory, entities (agents) are constituted by flows of tangible and intangible resources; these flows provide the capability for accessing further regimes of resources, for example in the form of knowledge, opportunity, and competitive advantage (c.f. Van den Bosch, Volberda and de Boer, 1999).

According to the theory of *dissipative structures* (Prigogine and Stengers, 1984), when this resource flow moves to a far-from-equilibrium dynamic, whole-system structures can emerge through the process of self-organization (Jantsch, 1980; Adams, 1988; Anderson, 1999a). In coevolutionary terms, environmental changes can spark major organizational transitions, leading to the “mutation of new organizational forms from the existing stock of organizations” (Lewin and Volberda, 1999: 529). A three-stage process of self-organized change has been used to explain the success or failure of entrepreneurial ventures in rapidly changing markets (Lichtenstein, 1998; Lichtenstein, 2000b); this model should be well suited for studying emerging order in coevolution.

An important question is under what circumstances coevolutionary change will be incremental or punctuated. According to Lewin, Long and Carroll (1999: 539-540), “During periods of relative stability, organizations and populations change and adapt in [incremental] ways, reinforcing the existing dominant organizational form.” In contrast, major environmental dynamism can generate self-organized transformative change, as long as certain path-dependencies are present. This is in fact an empirical question that can be usefully modeled by two other complexity disciplines. *Catastrophe theory* shows that virtually all adaptive change can be explained in terms of seven mathematical models; the most common is the “cusp catastrophe,” which essentially differentiates between continuous incremental change and discontinuous punctuated change (Bigelow, 1982; Gresov, Haveman and Oliva, 1993). Guastello (1995) has used all seven catastrophe models in his analyses of organizational behavior and change; and he has detailed an approach for accomplishing the nonlinear regressions of catastrophe theory by recasting each of the seven models as a complex statistical equation in SPSS.

A central aspect of *synergetics* which is also present in catastrophe theory, is the notion of an “order parameter.” In both theories, the system’s order parameter is the specific quality (variable or construct) that differentiates between linear and nonlinear change processes (Zuijderhoudt, 1990). The mathematics of synergetics, which were originally used to develop the laser (Haken, 1977), might be usefully applied to coevolution as a search for the condition or set of conditions that can trigger change and adaptation at the organizational, population, or cultural level.

According to Lewin, Long and Carroll (1999: 541), as organizations or populations adapt in highly dynamic environments, the successful ones will evolve to a critical balance point, “that balance between order (the pull of exploitation) and disorder (the pull of exploration) that is often called ‘the edge of chaos.’ At this point of dynamic tension, truly novel emergent behavior can occur.” Many complexity scholars equate organizing in this dynamic tension with the state of medial interdependence in an NK landscape (Brown and Eisenhardt, 1998; Anderson, 1999; Clippinger, 1999), others argue that the “edge of chaos” is a misnomer for social system behavior (Mitchell, Crutchfield & Hraber, 1994). Instead, this dynamic, self-organized behavior (Anderson, 1999a) might be better modeled in terms of *self-organized criticality* (Bak and Chen, 1991; Bak, 1996). A system in this state is highly adaptable yet stable, exhibiting mostly small changes interspersed with a few large-scale transformative shifts (Bak, 1996). Since the frequency of system changes over time takes the signature form of a power law (Bak and Chen, 1991), the mathematics of self-organized criticality may be useful for identifying how close a coevolving organization or population is to reaching that dynamic, self-organized state.

Finally, *emergent evolution* provides a broad theoretical foundation for coevolution, by explaining the contingent differences in institutional factors and "extra-institutional environments" in terms of a continuous expansion of developmental capacities conditioned by localized constraints (Jantsch, 1980; Leifer, 1989; Wilber, 1995; Swenson, 1997). Coevolutionary variation is represented by the emergence of new levels of self-organized order, which then undergo selection and retention according to the well-known processes of organizational evolution (White et al., 1997; Aldrich, 1999). As such, co-evolutionary change can be understood as a coherence of factors at multiple levels (individual, organizational, institutional, socio-cultural), with an overall direction of increased information, communication, trust, interdependence, and managerial development (Torbert, 1991; Wilber, 1995; 1998; Lichtenstein, 2000a). This optimistic yet challenging framework is well expressed in many of the managerial applications of complexity theory, which represent an important stream of research that is complementary to the more mathematical forms (e.g. Kelly and Allison, 1999; Lissack and Roos, 1999; Petzinger, 1999).

CONCLUSION

The interdependence of qualitative and quantitative research is equally important in coevolution as it is in complexity theory. For example, many of the empirical papers in the <u>Organization Science</u> special issue on "Co-evolution of strategy and new organizational forms" (Lewin and Volberda, 1999) utilize quantitative statistics, visual time series, and qualitative analyses to exemplify distinctions across a small number of cases (e.g. Koza and Lewin, 1999; Webb and Pettigrew, 1999). In these papers it is the bridging between qualitative and quantitative that informs and gives meaning to the analysis as a whole .

In the same way, the fullest interpretations and generalizable meanings of complexity theory may only be realized when mathematical modeling techniques are seen as complementary to case study analysis using careful operationalizations and analogical reasoning (e.g. Sorenson, 1997; Lichtenstein, 1998; McKelvey, 1999b). At present, this multi-disciplinary approach is not well developed; complexity research is being framed by many as a mathematical modeling endeavor. This bias is clearly cited by Morel and Ramanujam (1999: 289) who conclude their article by saying, "Application of complex systems theory to organization theory must rely on mathematically proven or computationally justified facts….Whenever dynamics is involved, there is no good alternative to mathematical modeling." [4]

However, this approach of theory-model development leaves out the complementary aspect of model-phenomenon testing (McKelvey, 1999c). As McKelvey has shown, both of these activities are interdependent and necessary in order to generate an overall theory that is epistemically realistic while retaining high face validity (McKelvey, 1999a). This argument certainly holds in coevolutionary research, which promises a rigorous analysis of multiple factors that can be leveraged to improve the adaptability and performance of firms and industries in hypercompetitive circumstances.

For these reasons, I am advocating for a multi-disciplinary approach to complexity, one that would include both the mathematical modelers and the qualitative researchers and all those in between. Furthermore, using the arguments from path dependence, by institutionalizing an openness to multi-disciplinary work at this early stage of paradigm development, we create an opportunity for unexpected approaches and collaborations to emerge over time. As a result I believe a matrix of complexity will increase the chances that

[4] Of the seven empirical or theory-building articles in the Organization Science special issue on complexity,

our insights about emergence and coevolution will become more than a fad, offering a significant contribution to academic scholars throughout the social sciences, and management practitioners throughout the business world.

six either utilize or operationalize mathematical simulations.

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TABLE 1: Summary of Complexity Disciplines for Understanding Emergence

RESEARCH STREAM	INSIGHTS FROM THEORY	MANAGERIAL INSIGHTS FROM THEORY	MANAGEMENT REFERENCES
Fractals	Natural systems exhibit self-similarity across scales, and can be rigorously measured using partial dimensional ("fractal") mapping.	Organizations exhibit self-similar behavior and/or values across levels (e.g. individual, group, company-wide.)	Zimmerman and Hurst, 1990
Deterministic Chaos Theory	Emergent order (attractors) can be identified in data that appears random. Dynamic systems are highly sensitive to initial conditions (i.e. Butterfly effect).	Strange attractors are "basins of attraction" toward which organizational behaviors tend. These attractors can be statistically identified in time series data. Changes in attractors may imply learning and/or organizational transformation.	Kiel, 1994; Thietart and Forgues, 1995; Cheng and Van de Ven, 1996
Self-Organized Criticality	Certain dynamic systems evolve to a state in which all changes are related through a single power-law.	Specific strategies and organizational processes can generate dynamic structuring at the "edge of chaos." This dynamic strategy/structure supports high innovation and creativity in organizations.	Carneiro, 1970; Stanley et al., 1996
NK Landscapes	Organisms and environment co-evolve. The "fitness" of an organism depends on the overall fitness of its environment, and vice versa.	An organization and its market environment co-evolve. The "fitness" of an organization depends on its environmental influence, and vice versa. Value chain relationships can be effectively modeled, and new value chain strategies generated, using this approach.	McKelvey, 1999b; Levinthal & Warglein, 1999; Fleming and Sorenson, 2001
Cellular Automata; Game Theory	Programmed entities (cellular automata) display complex emergent patterns as they evolve toward a critical value; this value became known as the "edge of chaos."	Strategic moves are constrained by the decisions/behaviors of one's immediate neighbors; these constraints generate emergent patterns in computer simulations.	Axelrod, 1984; 1987; Krugman, 1996
Simulated Annealing	Computer models simulate order that emerges in certain physical and/or chemical annealing processes	Organizational adaptation and learning can be modeled as a simulated annealing process, in which optimal moves are constrained and made possible by local conditions which change over time.	Carley and Svoboda, 1996; Carley, 1998
Synergetics	High-energy systems generate emergent order when linear changes in one parameter spark non-linear shifts in another.	The emergence of group behavior can be explained through shifts in "control" parameters that generate non-linear affects in organizational order.	Haken, 1984; Zuijderhoudt, 1990

Catastrophe Theory	Transformative change can be qualitatively modeled to show how incremental change across one parameter (variable) creates “catastrophic” (punctuated) changes across another.	Transformative organizational change can occur incrementally or in a punctuation. Re-analysis of behavioral data using non-linear catastrophe models explains up to 400% more variance than the same data analyzed using linear regression models.	Bigelow, 1982; Guastello, 1995; Gresov, et al., 1993
System Dynamics	Positive/negative feedback loops can be mapped, allowing for a systematic experimentation of dynamic conditions in very complex systems.	Multi-level dynamic interactions across systems can be modeled, showing how and why unexpected behavior occurs in complex systems. These models can be used to find “leverage” points that avoid unintended effects.	Hall, 1976; Sastry, 1997
Autogenesis/ Autopoiesis	Some dissipative structures can self-generate and self-replicate their internal order. Autogenic systems (like “mind” are self-organized and display emergent behavior.	Organizing processes self-replicate their internal order, based on a deep structure that generates rules and more visible operations. Rule creating and rule following behavior is an emergent, self-organized process.	Pantzar and Csanyi, 1991; Drazin and Sandelands, 1992
Complex Adaptive Systems	Interdependent semiautonomous agents, acting from even a few simple rules, generate emergent system behaviors.	Emergent organizational behavior may result naturally due to ongoing double interacts that follow from very simple rules. These emergent behaviors may be used for learning or to develop new strategies.	Holland, 1995; Dooley, 1997; Anderson, 1999b; Axelrod and Cohen, 2000.
Dissipative Structures	New levels of order self-organize in nonequilibrium dissipative structures. Emergence is a self-amplifying process sparked by fluctuations, resulting in greater system capacity.	Groups and organizational systems can maintain themselves at a high degree of structural order by dissipating large amounts of energy, information, and resources.	Smith, 1986; Wicken, 1986; Adams, 1988; Lichtenstein, in press.
Emergent Evolution	Evolution is a self-organizing process that creates new forms, which then undergo natural selection processes. The universe has experienced an increase in complexity across evolution.	Organizational co-evolution is a combination of variation-selection-retention and non-linear adaptation. Long-term development involves a multiple series of transformations, requiring action learning and transformations of managerial capability and development.	Leifer, 1989; Torbert, 1991; White et al., 1997; Wilber, 1998; Lichtenstein, 2000

TABLE 2: "The Matrix" of Complexity – One Typology of Disciplines

	Theory-Model Development	**Model-Phenomenon Testing**
Discovery of Order:	Fractals	Deterministic Chaos Theory
Modeling Emergent Order:	NK Landscapes Genetic Algorithms/ Cellular Automata Simulated Annealing Synergetics	NK Landscapes Self-Organized Criticality Catastrophe Theory System Dynamics Autogenesis/Autopoiesis
Intrinsic Emergence:	Complex Adaptive Systems	Dissipative Structures Emergent Evolution

FIGURE 1: McKelvey's Semantic Conception Of Organization Science