A Matrix of Complexity for Leadership:
14 Disciplines of Complex Systems Leadership Theory[•]

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INTRODUCTION

For some time, scholars have suggested that complexity research can play an important role in management theory generally (Simon, 1962; Schieve & Allen, 1982; Ulrich & Probst, 1984; Weick, 1977; Anderson, 1999; McKelvey, 1999a), and more specifically in explaining the dynamics of organizational change and adaptation (Zeleny, 1981; Bigelow, 1982; Goldstein, 1986; Nonaka, 1988; Smith & Gemmill, 1991; Carley & Prietula, 1994). Complexity-inspired research papers have appeared in virtually all of the top journals in management, reflecting an increasing ability for researchers to integrate the insights from these methods into mainstream organization theory (McKelvey, 2004b; Siggelkow & Rivkin, 2006; Plowman et al., 2007).

Leadership scholars have also been recognizing the potential value of complexity frameworks for exploring and explaining the interactive, generative, and emergent nature of leadership properties and processes (Guastello, 1998; Marion & Uhl-Bien, 2001; Uhl-Bien, Marion, & McKelvey, in press)). 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 increasingly important in explaining leadership in dynamic contexts (Lichtenstein et al., 2007; Plowman et al., in press). Additionally, complexity provides a framework for understanding adaptive order, innovation and emergence, issues that are becoming more central to leadership scholarship (Rivkin, 2000; Garud, Kumaraswamy, & Sambamurthy, 2006; Plowman et al., in press). These prospects have led to two recent special issues on Leadership and Complexity Theory, in ***The Leadership Quarterly***, and ***Emergence: Complexity and Organization,*** as well as two edited books – the present volume, and a companion volume edited by Uhl-Bein and Marion (in press).

One challenge with this stream of research is that it draws on a diverse range of models and wide number of approaches which, though different in many ways, all seem to fall under the banner of “complexity.” This confusion is increased when more popular and ‘metaphorical’ accounts of complexity are added to the mix (see (Maguire & McKelvey, 1999). Early enthusiasm about complexity sparked a proliferation of popular managerial articles and books that utilize complexity models to explain everything from strategy formation (Beinhocker, 1999; Stacy, 1992) to management practice (Lissack & Roos, 1999; Wheatley & Kellner-Rogers, 1996); from product development (Brown & Eisenhardt, 1998) to organizational development (Goldstein, 1994). This diversity in topic and in 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, 1999), and others consider it “collection of results, models, and methods” (Cohen, 1999: 375). Some place its origin in the European research of Ilya Prigogine (McKelvey, 2004a), others argue that complexity was formulated by scholars from the Santa Fe Institute (Waldrop, 1992); some mark its beginnings in the mathematics of deterministic chaos (Gleick, 1987; Kauffman, 1993), while others locate its source in cybernetics, dynamic systems modeling, and so on (Capra, 1996; Goldstein, 2000).

What is the essence of this diverse stream of complexity research, and should complexity be utilized to study leadership? More specifically, how can the multiple approaches to complexity be organized into a framework that would allow leadership scholars to match the right approach with the particular question they are asking (Davis, Eisenhardt, & Bingham, 2007)? In this brief review article I will offer one answer to these questions. I start by affirming the idea that “emergence” is the core issue which integrates the research being placed under the complexity banner (McKelvey, 2004). Next I outline two dimensions that can help organize the range of methods being utilized by complexity researchers. One dimension reflects the type of emergence being studied, and the other dimension reflects the levels of emergence being explored. Together these dimensions generate a typology – the matrix – that distinguishes 14 distinct complexity approaches. I then show how each of these approaches can support the development and testing of a complexity-based leadership 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 strengthen our academic scholarship, rather than continue to degenerate into a fad (McKelvey, 1999a).

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 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; Prigogine & Stengers, 1984; Lichtenstein, 2000a). 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 early 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 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) described a new synthesis of these models, based on research coming out of the Santa Fe Institute. At that point, “complexity” became the buzz word, referring to a well-received set of studies using computational agents (Cowan, Pines, & Meltzer, 1994; Holland, 1995; Kauffman, 1993), cellular automata (Axelrod & Bennett, 1993; Krugman, 1996) and other agent-based simulations (Carley, 1995, 1999) to understand emergence in new ways. (See Goldstein, 1999, 2000 for a complementary overview of the origins and elaboration of complexity.)

Each complexity theorist tends to specialize in one or two disciplinary methods for studying complex dynamical systems – this explains why complexity research appears so diverse. A key goal of this article is to connect and begin to integrate these various approaches, with an eye toward developing a more comprehensive and useful leadership theory based on complex systems. An overview of the breadth of these disciplinary approaches is presented in Table 1. The table is based on classic and recent 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; 2000), Marion (1999), McKelvey (1999a, 1999b, 2004a, 2004b), and Davis, et al. (2007); among others. 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. 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 identify the essence of these research streams, and organize them in a way that can support researchers in testing a complex systems leadership theory. Each of these 14 disciplines of complexity explores the conditions, properties, or processes of emergence in dynamic, complex systems, and they do it in different ways. Before describing these ways, I provide one definition of emergence.

At its essence, complexity researchers are providing new ways to understand *how and why order emerges* (Lichtenstein, 2000b; McKelvey, 2001, 2004a). Formally, emergence has been defined in terms of "qualitative novelty" (Blitz, 1992; Newman, 1996; Popper, 1926); emergence scholars focus on the creation of coherent structures in a dynamic system (Goldstein, 1999; 2000; Holland, 1994). When these emergent structures are different 'in kind' from the elements that compose them – when a new "level" of order has come into being, or a pattern of activity can be discerned that in some way *transcends but includes* the elements of the system, emergence can be said to have occurred. Thus, emergence is a 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).

Leaders routinely put enormous effort into supporting the emergence of higher-order structures in their organizations, and identifying and amplifying self-organizing patterns or structures that shift the nature of the organization in some way (Buckle-Hennings & Dugan, this volume). In addition, leaders themselves sometimes become identified through emergent processes (Guastello, 1998), and emergent events are often catalyzed by leadership activities originating from throughout the organization, including from senior managers (Plowman et al., in press). These dynamics and efforts have been understood and explained in a variety of different ways (e.g. Lichtenstein et al., 2007; Hazy, Millhiser & Solow, this volume; Goldstein, this volume). Why this variety? Beyond the obvious recognition that each research study explores slightly different phenomena using a different base of data, in each case the choice of complexity method itself comes with a set of assumptions that enable and constrain the insights which may be gained.

As Davis et al. (2007: 285) expressed for a limited subset of complexity models: "In fact, the choice of simulation approach may be closer to choosing a theoretical framework…because of its framing of research questions, key assumptions, and theoretical logic." Thus, one goal is to provide a framework for understanding the breadth of choices fully available to leadership scholars who are developing your own study of Complex Systems Leadership Theory.

TWO DIMENSIONS OF EMERGENCE

Each of the complexity disciplines listed in Table 1 explores and explains emergence in ways that crucially depend on a series of assumptions and goals which usually are unexamined. These fourteen disciplines reflect the entire spectrum of approaches that in any way refer to "complexity." Furthermore, rather than simply a listing of models, I aim to differentiate the 14 complexity disciplines according to (1) the type of emergence they produce (Crutchfield, 1994), and (2) levels or units of emergence they can capture. These two dimensions together generate a typology of emergence disciplines (see Table 2), which can help leadership scholars find the appropriate method for theory building and empirical testing. This typology is what I mean by a matrix of complexity.

Three Types of Emergence

The first dimension is presented by Crutchfield (1994), who distinguishes complexity theories according to the aspect or quality of emergence each seeks to explain: the **discovery of emergence**, the **modeling of emergence**, or **intrinsic emergence**.   The first type refers to the *discovery* that something new has appeared in a complex system. This something could be a pattern, a degree of order, or a structure. Fractal analysis or deterministic chaos theory fit into this category, for they both have been used to *discover* order across multiple scales or 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). 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) or through firm strategies (Rivkin, 2000). 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" (Smith & Gemmill, 1991; Browning, Beyer, & Shetler, 1995; Leifer, 1989; Lichtenstein, 2000a) fall into this category; as do a class of agent-based modeling approaches in which agents fundamentally extend their behavioral capabilities by learning over time (Gell-Mann, 1994; Macready and Meyer, 1999; Carley & Svoboda, 1996).

Please See Table 2--*Place about here*

Three Levels of Emergence

The second dimension refers to the *levels of emergence* that each method can usefully capture. The notion of "levels" has a long history in systems theory, where early researches identified a relatively coherent and common set of nested hierarchical levels that composed organisms, organizations, and societies e.g. (von Bertalanffy, 1968; Boulding, 1978; Miller, 1978; Salthe, 1985). Management scholars have long recognized the importance of levels of analysis in describing organizations (Kast & Rosenzweig, 1972; Rosen, 1974; Ashmos & Huber, 1987), and in grappling with the challenges of doing multi-level research (Rousseau, 1985; Dansereau, Yammarino, & Kohles, 1999; Davidsson & Wiklund, 2001). These challenges have led to limitations in our understanding of emergence; in entrepreneurship, for example, where emergence is recognized to be a central topic area, less than 0.05% of top tier articles over a 10-year period utilized both multi-level and non-retrospective longitudinal designs (Chandler & Lyon, 2001).

Examining more than a single level of analysis is implicit in the long-standing definition of emergence as "qualitative novelty," which refers to a shift in kind or type. This is exemplified in Mead's early characterization of emergence in terms of "…patterns or global-level structures [that] arise from interactive local-level processes" (Mead, 1932 in Mihata, 1997: 31). Based on this definition, the minimal exploration of emergence is the observation of a *pattern within* a single level of system interactions. For example, management researchers have used deterministic chaos theory to identify emerging order within organizational change processes (Dooley & Van de Ven, 1999) and organizational procedures (Kiel, 1994). Likewise, catastrophe theory has been used to identify change points and the dynamics of hysteresis in organizational transformations of all kinds (Bigelow, 1982; Guastello, 1995; Guastello, 1998). Similarly, computational studies using cellular automata and NK landscapes have detailed the processes whereby a new system-wide order emerges out of agent interactions, leading to intriguing findings around innovation systems (Fleming & Sorenson, 2001), economic geography (Sorenson & Audia, 2000), and strategic learning (Garud & Van de Ven, 2002; Siggelkow et al., 2006). Many other examples are provided in the summaries by Sorenson (2002) and Maguire and his colleagues (Maguire, McKelvey, Mirabeau, & Oztas, 2006).

A different set of methods highlight the novel dynamics that can arise out the interactions of agents in a system, thus focusing on *two levels of system activity*. More than an emergent pattern or structure that can be discerned within a system, these disciplines explore and explain how and when a new dynamic or level of order "arises" out of a system's lower-level components. For example, synergetics (Haken, 1977) offers a unique framework for examining "self-organized" patterns of activity that arise through the "enslavement" of system components to a higher-order resonance (Haken, 1984; Bushev, 1994). Separately, genetic algorithms are a tool for modeling the evolutionary learning of a system through unique combinations of system elements (traits) that generate a new dynamic within the system itself (Holland, 1998). In a different way, dissipative structures has been used to explain the emergence of new, coherent structures in a system (Leifer, 1989) which can transform its functionality and organizing capacity (Nonaka, 1994; Lichtenstein, 2000a).

Third, some complexity methods have been able to capture *multiple levels of activity*, which allow researchers to understand some of the underlying mechanisms of emergence in organizations. For example, power law analyses have shown how a systemic process or dynamic can generate multiple interdependent levels of order across organizations (Stanley, et al., 1996) and throughout social systems (Carniero, 1970). Agent-based modeling explains how agent interactions develop these interdependent levels of emergent order (Malerba, Nelson, Orsenigo, & Winter, 1999), and some multi-agent leaning models provide evidence that three or more levels of emergent hierarchy can self-organize given the right conditions (Carley, 1990, 1999);

(cf. McKelvey & Lichtenstein this volume). Finally emergent evolution shows how self-organized evolutionary processes can explain the breadth of development in biological (Weber & Depew, 1990) and social systems (Adams, 1988; Chiles, Meyer & Hench, 2004); and even more significantly, how the self-organization of a system is in some measure a reflection of the capacities of the leaders within that system (Wilber, 2001; Rooke & Torbert, 2005).

These two dimensions provide a matrix of complexity approaches, each of which can be classified as one of the "sciences" of complexity (Cohen, 1999). Next, I briefly suggest how each of these streams of complexity can be used to explore the dynamics of leadership from a complex systems perspective.

COMPLEXITY MODELS FOR LEADERSHIP

Advances in complexity science may help provide a much needed theoretical footing for leadership research. Many of the key processes in leadership—emergent processes, 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 outcome of Complex Systems Leadership Theory — enacting adaptive change through the interactions within and between all levels of organizational and environmental interactions — can be framed in terms of emergence, i.e. the coming-into-being of "macro patterns that depend on [continuously] shifting micro patterns" (Holland, 1998: 7). Emergence is a multi-dimensional feature and quality of systems; each discipline of complexity provides a unique view on the dynamics that reflect or generate emergent processes.

Discovering Order

Deterministic Chaos Theory. The new models of Complex Systems Leadership Theory focus on how leadership is enacted thorough interactions across an organizational system (Marion & Uhl-Bein, 2001). In most cases these interactions reflect and generate patterns of activity – a configuration of behaviors or models that are coherent over time (Dooley & Van de Ven, 1999). Although these patterns may appear stochastic on the surface, in fact they may be highly structured if mathematically complicated emergent processes which can only be discerned using tools like deterministic chaos theory (Baker & Gollub, 1996; Sulis & Combs, 1996). In a formal sense, mathematical tools like Lyapunov exponents, embedding dimensions and attractor reconstructions allow skilled researchers to rigorously identify these patterns amidst time series with at least 50 distinct data points (Guastello, 1995). Leadership scholars could use this framework to distinguish and detect even subtle patterns of interaction within a range of organizational interactions (e.g. Buckle-Henning & Dugan, this volume); or to identify specific bifurcation points in a significant system-wide shift of activity regimes (Cheng & Van de Ven, 1996). In an informal sense, leadership and organizational researchers have developed a metaphorical understanding of "complex attractor" as a configuration of activity over time (Marion, 1999). Identifying such configurations and tracking how they change may provide insight into how system-wide interactions influence changes in organizational behavior, while also reflecting path dependency and historical embeddedness leadership properties in the firm.

Catastrophe Theory. A different set of mathematical tools is helpful in explaining the transitions between one regime of stability (order) and a second or third regime, particularly when the shift from the one to the other is non-incremental. Thom (1975) and Zeeman (1977) developed a series of equations now known as *catastrophe theory* (Guastello, 1995), which describe system-wide, “catastrophic changes” in organizational behavior (Bigelow, 1982) and strategic design (Gresov, Haveman, & Oliva, 1993). Guastello (1998) used a four-dimensional model from catastrophe theory to describe three types of leaders that emerged in a series of four-person task groups; his “swallowtail” equation resulted in an R^2 of .9993 (with all variables significant at the .05 level). These results were replicated in a cross-cultural test using the same experimental conditions and a similar sample (Zaror & Guastello, 2000), suggesting that the emergence of leadership qualities may be a quality of the internal dynamics of the system itself, rather than due solely to environmental or contextual cues. Catastrophe is thus an excellent approach for identifying the rapid or discontinuous emergence of leadership qualities in a range of situations.

System Dynamics. A critical part of explaining interactions between and across levels is the feedback loops that are involved. “The goal of leadership 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 leadership research, and *system dynamics* provides a powerful means for modeling the non-linearities of these positive feedback systems. System dynamics forces researchers to carefully identify each feedback process within an entire system (Sastry, 1997); the rule-based computational model can reveal hidden interdependencies and emergent characteristics that are not tractable using linear thinking (Hall, 1976). The value of system dynamics for leadership is illustrated in Rudolph and Repenning’s (2002) analysis of system-wide forces – in this case an accumulation of non-normal events – that can overwhelm the processing capacity of even the most effective groups and their leaders.

Self-Organized Criticality. A different approach for modeling a dynamic system that evolves to a adaptive but stable state was developed by Bak and Chen (1991; Bak, 1996). The paradigm for their model is the well-known "sandpile" consisting of a stream of sand (representing any ongoing input to the system) dropping onto a plate with fixed diameter (representing a specific capacity that the system can reach). Once the sandpile has reached a specific size it will remain dynamically in a predictable range, exhibiting mostly small changes (avalanches) interspersed with a few large-scale transformative shifts (Bak, 1996). For example, Gunz, Lichtenstein & Long (2002) studied vacancy chains in three organizations and found that, as predicted by the model of *self-organized criticality [SOC]*, the size and frequency of vacancy chains followed the signature form of a power law (Bak and Chen, 1991). In this self-organized state large scale transformative changes are rare but normal (Gunz et al., 2002); thus leadership scholars could utilize *SOC* as a diagnostic tool for identifying how close an interaction system is to reaching that dynamic, self-organized state, and how the system might be "tuned" through shifts in the system conditions (i.e. in the 'diameter' of the sandpile).

Fractals. Just as SOC identifies patterns of behavior within a system, *fractal* mathematics allows for a careful mapping of subtle similarities across multiple system levels (Mandelbrot, 1983). These tools offer a framework for studying "self-similarity across scales" – patterns and dynamics that repeat themselves in specific ways as one extends outward from simple to increasingly encompassing systems. This approach has been used, for example, for exploring how change occurs in similar ways at the individual-, group-, departmental- and whole-organizational-level of analysis (Zimmerman & Hurst, 1993); and more recently for determining the efficacy of a company's information technology by exploring the "continued coherence" between organizational activities and IT capabilities across levels (Dhillon & Fabian, 2005). Such an approach is ideal for identifying which arenas in an organization display the characteristics of complex leadership versus areas that are less vibrant in those qualities, providing a unique tool for diagnosis and follow-up of new leadership programs.

Power Laws. A more formal approach for examining cross-level patterns of interaction is based on a simple but powerful premise: certain generative mechanisms of self-organization are scale-free – i.e. they operate across multiple orders of magnitude or system levels (McKelvey & Andriani, 2005). These scale-free dynamics can be readily discerned (and predicted) by charting their outcomes according to a simple formula which is described by an inverse power law (McKelvey, 2006). For example, Stanley and his colleagues (Stanley et al., 1996) find that a single scaling law accounts for the relationship between growth rates and internal structure of U.S. manufacturing companies between 1975 and 1991, across more than seven orders of magnitude (i.e. from companies with 10 employees to those with more than 100,000!). Similarly, Carneiro (1987)found a distinct generative mechanism that accounts for the growth dynamics of native villages regardless of size or region. Power laws thus reflect generative dynamics at multiple levels, a key quality of CSLT (Lichtenstein et al., 2007).

Modeling Emergent Order

Over the past two decades several sophisticated computational methods have developed that allow researchers to develop dynamic models of emergence processes and test them in highly controlled and repeatable ways. These models include a small number of specific research streams: cellular automata (Krugman, 1996), NK landscape models (Kauffman, 1993), Genetic Algorithms (Holland, 1995), and combinations of several approaches found in agent-based modeling (Carley, 1999; Malerba et al., 1999). Research studies within each stream encompass a range of capability, e.g. some genetic algorithm studies show the emergence of one new level of order from agent interactions, while others suggest the emergence of two or more levels of order. On average, however – and for the sake of simplicity – these streams may be provisionally categorized within a specific cell. You the reader may disagree, and I welcome your expertise and interaction on these specifics (please e-mail me at benymain.bml@gmail.com.) The more learning we can do together the more likely we all will gain success in our efforts to build a science of complexity for leadership and management.

Cellular automata. Early computational approaches explored what happens when a set of agents situated in a linear or a 2-dimensional matrix evolves based on the decisions of its (nearest) neighbors (e.g. Schelling, 1978). It turns out that even small initial differences in preferences or traits tend to aggregate, leading to a consistent degree of order across the system. Although technically this order is expressed as a visible pattern within the system, some advanced applications have interpreted this emergent pattern to represent a new level. For example, economist Krugman (1996) uses a simple CA application of spatial modeling, to ask why “edge cities” form, and whether their distribution can be explained through a power law. He finds that randomly dispersed business activities will always evolve into highly ordered edge cities that are ontologically distinct from their component businesses. Axelrod and Bennett (1993), using a “spin-glass” type CA landscape model to study group formation; applying the model to 1939 data, they accurately predict the political alliance formation of all but one nation during WWII.

This approach could augment leadership research by examining the relationship between individual agent moves (e.g. initiating a project) and the responses of that agent’s immediate neighbors. Such studies might find how local reactions to emergent change processes can either catalyze or inhibit a good idea from diffusing successfully, and thus how the quality of emergent leadership crucially depends on spatial effects as much as internal networks, power dynamics, and so on.

NK Landscapes. By specifying two additional parameters to the basic cellular automata computational system, Kauffman (1993) developed a dynamic modeling tool that shows how internal structures can emerge in a system through the adaptive changes of its component agents. In this approach each cell is an agent with *N* traits or attributes that can change over time. At every time step each agent draws from its nearby neighbors a combination of attributes which appear to be most adaptive in the local neighborhood. Overall, agents' attributes are interdependent *(K)*, such that the higher the *K* the more a change in one attribute will effect changes in other attributes. After a short number of iterations an internal structure emerges in the landscape, reflecting those combinations of attributes that are most and least adaptive relative to all others. As ‘everyone’ knows, the degree of order in the overall landscape crucially depends on the level of *K*, the degree of interdependence across the system (Kauffman, 1993). The general insight is that some measure of connectedness brings the entire system to a higher level of fitness and adaptability, but too much interconnection can lock the system into a “catastrophe” of interdependence (Sorenson, 1997; McKelvey, 1999c).

One exemplary use of the *NK* model for studying Type 1 emergence is Fleming and Sorenson’s (2001) study of technological invention. Treating invention as a re-combination of existing components in a given field, they show that the usefulness of an invention (measured as the 6-year citation count) “…can be maximized by working with a large number of components that interact to an intermediate degree” (Fleming & Sorenson, 2001: 1025). Other management scholars have utilized the *NK* model to study the adaptiveness of strategies in a dynamic industry

(McKelvey, 1999; Sorenson, 1997), the corporate performance contribution of cognitive vs. experiential learning (Gavetti and Levinthal, 2000; Gavetti, Levinthal & Rivkin, 2005) and the ways that organizational design and decision-making effect organizational outcomes (Rivkin & Siggelkow, 2003; Siggelkow & Rivkin, 2005).

There is not actually very much emergence, per se, in the *NK* model (Lichtenstein & McKelvey, 2005). For the most part, self-organization is limited to agent connections (networks) with nearest neighbors. In this respect most *NK* models detail how patterns emerge within a specific system; Level 1 Emergence, with the capability of advancing into Level 2 Emergence. According to recent reviews (Eisenhardt & Bhatia, 2002; Maguire et al., 2006), the vast majority of complexity studies utilize *NK* models and other computational experiments to show how emergent networks materialize within and across complex adaptive systems. At the same time, complexity leadership scholars can gain insight into the optimal combination of qualities (number and degree of interdependence) that could generate an ecology of innovation in a firm (Surie & Hazy, 2007), or to explore which and how many specific leadership "moves" (micro-processes or interventions) lead to successful organizational changes.

Genetic Algorithms. An important advance in modeling emergence occurs through the use of genetic algorithms, invented by Holland (1975, 1995). In the computational models identified up to here, agents have the capacity to change their attributes over time – they can learn (Carley and Hill, 2000), innovate new products (Fleming & Sorenson, 2001), and develop new strategies (Gavetti et al., 2005;) – yet they necessarily interact according to rules that are programmed into the system. In contrast, genetic algorithms (GAs) allow agents with multiple rules to change the rule strings governing their behavior (Macy & Skvoretz, 1998). As agents in horizontal networks co-evolve toward improved adaptive capability, differentiated groups emerge; soon thereafter group norms also solidify. Holland (1998: 190-191) describes how aggregates of new rules can represent “macro-laws” at a higher “level” of order:

> Just what is a new level in a *cgp?* The answer turns on one of the basic properties of a *cgp:* the possibility of combining mechanisms to make a more complex mechanism. … the resulting composite [is] subassembly that can be used to form still more complex mechanisms. …We have moved up one level of description.

GAs have been applied in a range of models. For example, Paul, Butler, Pearlson & Whinston, (1996) examine the adaptation of emergent financial trading firms (groups) and find combinations of increasingly better performing agents across prior periods. Crowston’s (1996) GA model shows that organizations and/or their employee agents can minimize coordination costs by organizing in particular ways. GA models can show how emergent behaviors of agents adapts and changes in a coevolving context (Holland, 1998). Here, agent moves (i.e. changes) are leadership moves, thus allowing leadership scholars to explore how, in complex 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 leadership process” (Axelrod and Cohen, 2000: 8). Equally important, GA models 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)

Agent-Based and Multi-Agent Learning Models. Carley and her colleagues have produced some of the more sophisticated models to date in computational modeling, which combine elements of CA, GA, and neural networks. In her CONSTRUCT (1991) and CONSTRUCT-O models (Carley & Hill, 2001), simulated agents have a position or role in a social network and a mental model consisting of knowledge about other agents. Agents communicate and learn from others with similar types of knowledge. CONSTRUCT-O allows for the rapid formation of subgroups and the emergence of culture, which, when it crystallizes, supervenes to alter agent coevolution and search for improved performance. These models show the emergence of communication networks (one level) and the formation of stable hierarchical groups (2 levels); they also show how higher levels of order "supervene" to influence lower-level behavior. Supervenience, the mechanism by which higher-level components intervene to alter the behavior of their lower-level components, has been called a crucial characteristic of emergence (Klee, 1984; Blitz, 1992).

Quite possibly the most famous example of "bottom-up" agent-based modeling is Epstein and Axtell's *Growing Artificial Societies* (1996). They boil their agent behavior down to a single rule: "Look around as far as your vision permits, find the spot with the most sugar, go there and eat the sugar" (p. 6). Agents search on a CA landscape and come to hold genetic-identity-culture identification tags according to a GA. This model not only builds social networks (one level), but also higher-level groups emerge (2 levels). These groups develop cultural properties that can supervene to alter the behavior and groupings of agents (three levels). Another sophisticated agent model is Carley's (1990, 1999) complex ORGAHEAD *Model.* This simulation consists of small groups of interacting workers (agents) led by an executive team that develops firm-level strategy based on environmental inputs. Groups that emerge in this model control who agents will interact with, learn from, and so on, thereby altering subsequent co-evolutionary emergence. Also, the emergent culture alters the knowledge-creation strategies of agents. In these ways Carley's model reflects three levels of order. Each of these, and many others, provide intriguing examples of how agent moves (leadership) at one level affect the structure and context for further moves (learning and leadership) at higher levels.

Intrinsic Emergence

In contrast to the computational and mathematical approaches described thus far, the disciplines which explore intrinsic emergence are from philosophical biology (Autopoiesis), thermodynamic chemistry (dissipative structures) and evolutionary theory (emergent evolution). Insofar as these disciplines are rigorously applied to organizations and management they exhibit the features of intrinsic emergence, i.e. their physical expression (realization) of emergence is not a model of something else, but itself generates a new level (or pattern) of tangible system order in real time.

Autogenesis/Autopoiesis. Deep structures and resource flows are at the heart of *autogenesis* and *Autopoiesis.* Both of these theories focus on how an autonomous system – an agent – produces its internal structures through a regenerative organizing process. The original theory, Autopoiesis (Maturana & Valera, 1980), explained how and why we experience ourselves as autonomous beings even though we are inextricably linked to an external environment. Their argument, which results in a unique material definition of life, is based on a definition and analysis of "structural coupling," which is a dynamic mechanism that links internal response to messages that (appear to) derive from the environment. This approach was drawn out in the social sciences through autogenesis (Csanyi & Kampis, 1985; Panzar & Csanyi, 1991), which explores identity-making processes in which an agent's core values and schemas define the rules that formulate emergent structures (Drazin and Sandelands, 1992) and social structures (Kickert, 1993). The value of autogenesis/autopoiesis is its conceptualization of the mutual causality – structural coupling – of resource flows and environmental potentials (Swenson, 1992; Swenson, 1997); understanding these flows provide the capability for accessing further regimes of resources, for example in the form of knowledge, opportunity, and competitive advantage.

Autopoiesis provides a useful model for understanding how one's leadership is a reflection of one's own internal perceptions and sense-making. In particular, the theory helps explain why our interpretations of the world and those powerfully felt impulses to make change based on those interpretations, are driven by internal patterns and psychological structures as much as by external events (Manz & Neck, 2004). In common parlance, Autopoiesis provides the theoretical underpinning for the well-known dictum: "believing is seeing" (Weick, 1979). This effect is crucial in the context of pattern recognition (Buckle-Henning & Dugin, this volume) and a systems view of leadership, for it helps identify how patterns that a leader perceives are in some ways also reflected in the perceiver. Disentangling this bias can highlight subtle elements of the pattern, with positive effects for getting at the heart of system's dynamics .

Dissipative Structures. Perhaps the best known and most utilized non-computational complexity model is drawn from Prigogine's Nobel-Prize winning work on how order is spontaneously created in far-from-equilibrium systems (Prigogine 1955; Prigogine & Glansdorf, 1971). According to their theory of *dissipative structures* (Prigogine and Stengers, 1984), when increasing resource flows cause a focal system to shift from near-equilibrium to far-from-equilibrium dynamics, a new level of macro-structures can spontaneously in the focal system (Bénard, 1901; Prigogine, 1955; Nicolis & Prigogine, 1989). In a formal sense, these "macro-structures" increase the capacity of the system to dissipate resources (heat); according to one set of experiments, the new level of order expands the system's processing capacity by several orders of magnitude (Swenson, 1989; 1991).

Swenson himself was an entrepreneur who created a successful small business that was one of the first to commercially produce and sell a new kind of cereal in the 1960s: Granola. Swenson's understanding of how dissipative structures can generate and explain organizational growth is comparable to many researchers who have applied the dissipative structures model to entrepreneurship (Binks & Vale, 1990; Foster, 2000), innovation (Dosi & Fagiolo, 1998; Saviotti & Mani, 1998), group dynamics (Smith, 1986; Smith & Comer, 1994), and economics in general (Georgescu-Roegen, 1971; De Vany, 1996). In management this approach has been used to explain the emergence of order in high-growth entrepreneurial ventures (Lichtenstein, 2000a); the emergence of a new dominant logic for strategy (Bettis & Prahalad, 1995), transformative change in strategy (Garud et al., 2002; MacIntosh & MacLean, 1999) and organization (Goldstein, 1994; Leifer, 1989), the emergence of industry-level collaborative ventures (Browning et al., 1995), the emergence of sustainable economic regions (Chiles, Meyer, & Hench, 2004), and so on.

A dissipative structures model is well suited for studying emergent order in leadership. On one level, the conditions that spark order creation in dissipative structures (Smith & Gemmill, 1991) are strongly connected to the conditions that spark adaptive and emergent leadership from a complexity perspective (Marion et al., 2001; Surie & Hazy, this volume, Plowman & Duchon, this volume). Furthermore, studies have shown that periods of internal order creation that often accompany innovation and rapid growth may be facilitated by a broader view of interaction-based leadership that is supported by a Complex Systems Leadership Theory (e.g. Garud & Karnøe, 2003; Lichtenstein & Jones, 2004). Even more broadly, the kind of systemic approach to leading that is the foundation of a complexity-inspired leadership is also at the core of dissipative structures (Artigiani, 1987; Goldstein, 1986). Using this approach to explore how to lead systemically as well as how to let the system lead would contribute to the dissipative structures model as much as to complexity leadership.

Emergent evolution is perhaps the least known stream in complexity science, but it offers perhaps the most profound implications for leadership, change, and social integration of all the complexity models. At its core, the theory of emergent evolution theory argues that biological and social evolution are best represented as an ongoing emergence of increasingly complex layers of macro-systems, each layer providing important gains in the system's capacity to operate effectively in it's environment. *Emergent evolution* provides the only complete account of evolutionary dynamics that compares with traditional neo-Darwinism (see Depew & Weber, 1985; Depew & Weber, 1995), and it is the only one that can successfully integrate physical, biological, social and cultural evolution through a single mechanism. This account was first written by Jantsch (1980); deeper explanations and contributions to this stream have continued to the present in Wicken, (1986), Lazslo (1987), Adams (1988), Weber, Depew and Smith's important compilation in (1990), Swenson (1992), Coren, (1998), Chaisson, (2001), and others.

In the context of leadership, this approach makes the strong claim that organizational development is a reflection of one's internal development – internal and the external processes of change are inextricably linked (Wilber, 1995, 2001). Management authors have also made this claim, albeit from a slightly different theoretical framework (e.g. Bartunek, Gordon, & Weathersby, 1983; Senge, 1990; Torbert, 1991; 2004). In my view, leadership is represented by the emergence of new levels of order, whose development increases the potential for others to grow and change as well (Fisher, Rooke, & Torbert, 2003). As such, leadership involves the influence of internal factors as much as external ones, and progresses in an overall direction of increased information, communication, trust, interdependence, and managerial development (Torbert, 1991; Wilber, 1995; 1998; Lichtenstein, 2000c). This optimistic yet challenging framework is also expressed in a few of the managerial applications of leadership and complexity (e.g. McMaster, 1995; Jaworski, 1998; Petzinger, 1999).

CONCLUSION

Developing a Complex Systems Theory of Leadership is conceptually challenging; at least we now have a set of analytic tools that can significantly improve ability to understand and explain how leadership emerges in interactions. The purpose of this essay has been to make more clear the distinct benefits of using these tools, and equally important, to highlight the vast array of disciplines that are at our disposal in the process. Unfortunately management scholars seem to hold a relatively limited view as to this range of options, as Davis et al. (2007) inadvertently made clear. The more options, the more likely a researcher will choose the model which best analyzes their research questions.

In fact, there is more at stake than which discipline to use. Leadership is a rich and nuanced phenomena, and a new era of leadership will require a combination of in-depth, richly qualitative studies along with precisely operationalized quantitative and simulation-based methods. As other complexity scholars have argued, the fullest interpretations and meanings from complexity may only be realized when mathematical modeling is a complement to case study analyses which use careful operationalizations and analogical reasoning (Lichtenstein, 2000d; McKelvey, 1999b; Sorenson, 1997). Only through this combination of qualitative and quantitative is a Complex Systems Theory of Leadership likely to reach its potential.

Unfortunately such a multi-disciplinary approach is not well developed yet; complexity research is framed by many as a purely mathematical or computational endeavor. This bias is 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." However, this approach of theory-model development leaves out the complementary aspect of model-phenomenon testing (McKelvey, 2002). 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 leadership research, which involves subtle internal processes and arenas that do not necessarily resolve into easily operational decisions.

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 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 our insights about complexity leadership will become more than another fad, offering a significant contribution to academic scholars and management practitioners throughout the world.

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TABLE 1: Summary of Complexity Disciplines for Understanding Emergence

RESEARCH STREAM	INSIGHTS FROM THEORY	MANAGERIAL INSIGHTS FROM THEORY	MANAGEMENT REFERENCES
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
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; Rudolph & Repenning, 2002
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.	Bak & Chen, 1991;
Fractals	Natural systems exhibit self-similarity across scales, whose dimensionality can be measured using a mathematical mapping technique.	Organizations exhibit self-similar behavior and/or values across levels (e.g. individual, group, company-wide.)	Zimmerman and Hurst, 1990
Power Laws	Certain processes repeat themselves across many scales; these repetitions can be identified through their unique signature (power law).	Many seemingly distinct organizational phenomena are inherently related to each other through a single set of underlying causal dynamics.	Carneiro, 1970; Stanley et al., 1996

RESEARCH STREAM	INSIGHTS FROM THEORY	MANAGERIAL INSIGHTS FROM THEORY	MANAGEMENT REFERENCES
Cellular Automata	The physical closeness/distance of agents significantly affects the dynamics of their evolution.	Macro-level structures are determined in part by spatial qualities of a field including e.g. density, proximity, and size.	Shelling, 1971; Lomi & Larson, 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
Genetic Algorithms	Programmed entities (cellular automata) display complex emergent patterns as they evolve toward a critical value.	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, Holland, 1995; Axelrod and Cohen, 2000.
Agent-Based and Multi-Agent Learning Models	Multiple algorithms can be linked in a single model, allowing researchers to explore complex phenomena.	Organizational adaptation and learning evolve through optimal moves which are constrained and made possible by agent qualities (e.g. knowledge) and local conditions (e.g. dynamism) that change over time.	Carley, 1990; 1999; Carley and Svoboda, 1996; Epstein & Axtell, 1996.
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
Dissipative Structures	New levels of order can spontaneously emerge in non-equilibrium situations, through a self-amplifying process sparked by fluctuations, resulting in greater system capacity.	Groups and organizational systems can generate new order or maintain themselves at a high degree of order by dissipating large amounts of energy, information, and resources.	Smith, 1986; Wicken, 1986; Adams, 1988; Lichtenstein, 2000.
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 multiple transforms, that can be achieved through action learning and managerial capacity and development.	Leifer, 1989; White et al., 1997;

TABLE 2: The Matrix of Complexity – A Typology of Complexity Disciplines

	Emergent Patterns within One System Level	**Emergent Dynamics within a System (two levels)**	**Principles of Emergence (three or more levels)**
Discovery of Order:	Deterministic Chaos Theory	Catastrophe Theory System Dynamics Self-Organized Criticality	Fractal analysis Power Laws
Modeling Emergent Order:	Cellular Automata NK Landscapes	Genetic Algorithms	Agent-Based Modeling
Intrinsic Emergence:	Autopoiesis/Autogenesis	Dissipative Structures	Multi-Agent Learning Models Emergent Evolution