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Gary M Grobman
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COMPLEXITY THEORY: A NEW WAY TO LOOK AT ORGANIZATIONAL CHANGE

GARY M. GROBMAN
The Pennsylvania State University Harrisburg

ABSTRACT

There is a revolution in the physical sciences with applying new theories that emphasize holism, uncertainty, and nonlinearity and that de-emphasize reductionism, predictability and linearity. The interest is growing in applying these theories to the study of organizations, including public organizations. The classic model of the organization as a machine has long since been discredited, but the models that have replaced this metaphor have been less than satisfactory. The basic principles of complexity theory are explained using organizations as examples. Complexity theory suggests that organizational managers promote bringing their organizations to the "edge of chaos" rather than troubleshooting, to trust workers to self-organize to solve problems, to encourage rather than banish informal communications networks, to "go with the flow" rather than script procedures, to build in some redundancy and slack resources, and to induce a healthy level of tension and anxiety in the organization to promote creativity and maximize organizational effectiveness.

INTRODUCTION

During the last decade of the 20th century, new theories to explain phenomena in the physical world, such as chaos theory, complexity theory, catastrophe theory, self-organized criticality theory, and nonlinear dynamics systems theory, have gained increased credence. There is growing interest in applying these new perspectives to organizations, including public organizations.

One motivation for this growing interest is the revolution in theory in the fields of physics and biology. New theories that emphasize uncertainty and randomness and that relegate reductionism and predictability to second-class status have changed how scientists look at the universe.

For example, natural phenomena such as radioactive decay are not seen as deterministic, but rather probabilistic. Schrödinger's equations permit one to calculate the probability that an electron will be found at some point away from a proton, but not where it will be in the future with any certainty (Adler, 2000). The Heisenberg uncertainty principle (Imamura, 1999) states that one cannot simultaneously measure the position of a particle and its momentum. In what appears to be a contradiction, matter acts simultaneously as both particles and waves (e.g., photons acting as particles when they bounce off a mirror, and acting as waves when they create interference patterns as they pass through pinholes.

Einstein showed that matter and energy are interconvertible and that time is a useful construct, but not an absolute. In biology, evolution is viewed today as not the slow, steady march as once described, but rather punctuated by revolutionary advances followed by ephemeral stability.

The roots of much of traditional organizational theory have as their basis metaphors based on scientific principles from the physical sciences (Morgan, 1997). Many have written about the inability of organization theory to explain and predict. The new ways physicists have of looking at natural phenomena may have promise in explaining why our old ways of looking at organizations are unsatisfactory. Why do organizations with nearly identical components have divergent results? Why do public organizations that put redundancy into their work processes or promote slack resources (see Kearney, Feldman, and Scavo, 2000), apparently wasting precious human capital, appear to do better—and how does this relate to redundancy in biological systems, such as brains, DNA, and other systems of living organisms?

Complexity theory and other theories relating to non-linear dynamic systems, may help provide an answer.

> Although traditional approaches to the explanation of organizational change and transformation processes are limited and have proven unsatisfactory in guiding both research efforts and applied management practices, it is suggested that these limitations may be lessened at a theoretical level by developments in the complexity sciences.... The complexity approach offers a fundamentally new way of conceptualizing many of the apparent paradoxes confronting organization theory and analysis (Mathews, 1999, p. 439).

The purpose of this paper is to explore a relatively new, interdisciplinary theory and discuss how it is being applied to the management and design of organizations. Complexity theory is revolutionizing the way scientists look at the world, and has ontological implications as well. While there is a healthy debate in the academic literature as to whether complexity theory is a totally new paradigm or simply an extension of general systems theory (see Bertalanffy, 1968; Katz and Kahn, 1966), I would suggest that there is something more going on here than systems adapting to their environment. Complexity theory provides a framework for theorizing about how there got to be an organization and an environment in the first place so that general systems theory could be applied.

An exploration of chaos and complexity theory can be intimidating, particularly to those without the science and mathematics background on which the foundation of these theories is laid. Not helping any is the fact that an esoteric, arcane lingo of technical terms permeates the literature.

Yet if there was nothing to these theories and the conventional ones were so wonderful, one might expect that predictions about the future would be easy to make. Planning would simply require seeing where you were now, putting future inputs into the equation, and cranking out the answer as to where the organization will be at any future time. Most of us know better than to accept the deterministic, reductionist paradigm at face value and expect to apply it with impunity. Our unwillingness to depend on the old paradigm is reflected in an old Yiddish expression, "If you want to make God laugh, tell Him your plans."

Why has complexity theory attracted so much attention lately?

> There are dramatic changes occurring in the structure and scope of business, governmental, and nonprofit organizations. The list of challenges for contemporary organizations is long: globalization, process reengineering, workforce diversity, quality improvement, and public service privatization are but a few. Such transformations in turn press organizations to put a premium on responsiveness to change. In an environment that seems to be changing, organizations want to be more adaptable and better able to learn from experience in order to reconfigure themselves in the face of new demands (Cohen, 1999, p. 373).

Cohen goes on to give other reasons as well: the acceleration of information technology revolution and its taxing of our ability to process information and data, and the degree to which organizations are being created, dismembered, and dismantled. The boundaries of organizations have been permeated through the use of virtual organizations, consultants, outsourcing, temporary hires, and ad hoc teams. Some of these developments can be described easily using the concepts of complexity theory, which, along with chaos theory, are useful in describing the rapid transformations undergone by non-linear dynamic systems such as organizations. Cohen's perspective is echoed by Lewis:

> The pressures for change in organizations have never been greater. Innovate or die is especially true, and this applies not just to technology but also to differing forms of organizational structure and processes....Chaos theory, and now its offshoot, complexity theory, offers all those in organizations clarity and a method of enhancing the management of change. These implications have not been developed in depth yet, but they are there (Lewis, 1994, p. 16).

Organization theorists in the academic community have awakened to the trend of increased interest in applying complexity theory to organizations. In 1996, the professional peer-reviewed journal *Organization Science* had a winter conference to "explore the implications of the science of complexity for the field of organization studies" (Lewin, 1999, p. 215). Twenty-two papers were submitted to a meeting called subsequent to that conference, and 56 papers were submitted to *Organization Science*. The entire May-June issue of this Journal was devoted to the subject, and included seven articles.

ORGANIZATIONAL DESIGN PRINCIPLES

Inherent in the concept of designing organizations is the notion that the designer explicitly incorporates design principles that presumably will make the organization perform better. The number of possible designs, as with the architecture of a physical structure, is potentially infinite. However, some of the basic designs that have become popular during the modern age are based on how scientists perceive the design of nature and the physical universe.

In the beginning of the 20^{th} century, the dominant metaphor applying to the design of organizations was that of a machine (see Weber, 1946; Taylor 1911). Bureaucratic hierarchies, centralized control, discipline, division of labor, organizational charts, standardized tools and procedures, emphasis on planning rather than improvisation, and minimal relationships to those outside of the organization—a closed system perspective—are artifacts of this view of organization (Morgan, 1997; Plsek, Lindberg and Zimmerman, 1997). This perspective utilizes the dominant paradigm of science, the view of a clockwork universe that was prevalent for much of the 18^{th} and 19^{th} centuries. It consisted of parts that worked together in a deterministic way. Given initial conditions, one could predict with accuracy where any system would be a second, or a millennium, from now. This Newtonian model remains valid if one has the task of predicting an eclipse involving the planets, or the flight of a ball traveling substantially less than the speed of light. Under this paradigm, the world is viewed as both deterministic and reductionist. In the 21^{st} century, we are just beginning to recognize its limitations.

> The Newtonian perspective assumes that all can be explained by the careful examination of the parts. Yet that does not work for many aspects of human behavior. We have all experienced situations in which the whole is not the sum of the parts—where we cannot explain the outcomes of a situation by studying the individual elements. For example, when a natural disaster strikes a community, we have seen spontaneous organization where there is no obvious leader, controller or designer. In these contexts, we find groups of people create outcomes and have impacts which are far greater than would have been predicted by summing up the resources and skills available within the group. In these cases, there is self-organization in which outcomes emerge which are highly dependent on the relationships and context rather than merely the parts. Stuart Kauffman calls this 'order for free' and Kevin Kelly refers to it 'creating something out of nothing' (Zimmerman, 1999).

In some ways, complexity theory is an extension of General Systems Theory, which became the dominant model of organizational theory in the 1960s. The dominant paradigm for decades was reductionist, suggesting that a system can be analyzed by understanding each of its parts, and that there was a general linear relationship between inputs and outputs. Experiments by a meteorologist, Edward Lorenz, initially based on a mathematical model used to predict weather, suggested that almost infinitesimal changes in initial conditions can drastically change the behavior of the entire system, the so-called "butterfly" effect. Complex systems demonstrate this nonlinearity because each component interacts with others via a web of feedback loops (Anderson, 1999, p. 217).

> ...the behavior of complex processes can be quite sensitive to initial conditions, so that two entities with very similar initial states can follow radically divergent paths over time. Consequently, historical accidents may 'tip' outcomes strongly in a particular direction (Anderson, p. 217).

One other feature of organizations explained by chaos and complexity theory is the appearance of scaling, a natural phenomenon that is best described as having fractal qualities. There is a structure of "roughness" to quantitative data involving an organization that looks the same, whether the data is on a scale of days, months or years. In nature, one sees this in the structure of a tree, a cloud, a weather pattern, or a coastline—it cannot be determined whether one is looking at a foot of coastline or a mile of coastline because the pattern appears to be the same regardless of scale.

By the beginning of the second half of the 20th century, general systems theory and its biological orientation took over as the dominant paradigm of organization theory, developing from the work of biologists such as Ludwig von Bertalanffy (Reed, 1996).

> By the late 1940s and early 1950s, this conception of organizations as social systems geared to the integrative and survival 'needs' of the larger societal orders of which they

> were constituent elements established itself as the dominant theoretical framework within organizational analysis. It converged with theoretical movements in 'general systems theory', as originally developed in biology and physics...which provided considerable conceptual inspiration for the subsequent development of socio-technical systems theory... (Reed, 1996, p. 37).

Even if the lingo and principles of the science of nonlinear dynamics as applied to organizations have not quite been embraced by the academic establishment, it is quite clear that the old clockwork paradigm is regarded as passé.

> Organizations are now routinely viewed as dynamic systems of adaptation and evolution that contain multiple parts which interact with one another and the environment (Morel and Ramanujam, 1999).

To many organizational theorists, neither the machine nor open systems models adequately explain observable behavior of organizations. Well-known writers in the field of public administration, such as Simon (1997) and Lindblom (1959), have pointed out the complexity of decision-making in organizations, and the limitations of rational decision-making and general management principles. Simon (1946) laments the fact that many of the general principles of public administration are contradictory and internally inconsistent. It is no longer considered strange to read in the literature about organizational effectiveness as being described by variables that are either contradictory, or even paradoxical. Cameron writes about this explicitly: "To be effective, an organization must possess attributes that are simultaneously contradictory, even mutually exclusive" (Cameron, p. 545). Thus organizations can have attributes that are contradictory and are paradoxical (1).

Using this framework, organizations can be both centralized and decentralized, both general and specialist, have both stability and adaptability, and diversified while "sticking to their knitting."

Complexity theory, particularly when used to explain the survivability and adaptability of biological systems, makes use of paradoxical explanations, many of which appear to have applicability to describing all complex adaptive systems, such as organizations. This new framework conflicts directly with the traditional metaphors or organizations, and parallels the replacement of metaphors by physical scientists.

> Science is replacing its old metaphors not so much because they were wrong, but because they only described simplistic situations that progress has moved us well beyond...our organizations today are not simple machines that they were envisioned to be in the Industrial Revolution that saw the birth of scientific management. Further, people today are no longer compliant 'cogs in the machine' that we once thought them to be. Management innovations such as learning organizations, total quality, empowerment, and so on were introduced to overcome the increasing visible failures of the simple organization-as-machine metaphor (Plsek, Lindberg and Zimmerman, 1997, p. 18).

DEFINITION OF A COMPLEX ADAPTIVE SYSTEM

A good working definition of a complex adaptive system is:

> A system of individual agents, who have freedom to act in ways that are not always predictable, and whose actions are interconnected such that one agent's actions changes the context for other agents (Plsek, Lindberg and Zimmerman, 1997).

Holland (1995) adds that these agents interact using rules that change over time as a result of the agents' experience. Adaptation occurs as agents adapt to the perceived rules of other agents. In the language of complexity theory, these rules are called "schema." When applied to the human context, the rules mean mental models of reality of the individual human agent. For example, a market economy CAS consists of individuals following a rule, which may be maximizing their personal utility functions.

> What is a complex adaptive system (CAS)? The three words in the name are each significant in the definition. 'Complex' implies diversity—a great number of connections between a wide variety of elements. 'Adaptive' suggests the capacity to alter or change—the ability to learn from experience. A 'system' is a set of connected or interdependent things. The 'things' in a CAS are independent agents. An agent may be a person, a molecule, a species, or an organization among many others. These

agents act based on local knowledge and conditions. Their individual moves are not controlled by a central body, master neuron or CEO. A CAS has a densely connected web of interacting agents each operating from their own schema or local knowledge. In human systems, schemata are the mental models which an individual uses to make sense of their world (Zimmerman, 1999).

WHAT IS COMPLEXITY?

In rough terms, the definition of complexity in the context of complexity science is the length of the smallest description that could be used to describe a system (Gell-Mann, 1994).

In a computer, a long string of binary data (i.e. consisting of zeros or ones) can be simple or complex, regardless of the length of the string. A string consisting of a million zeros could be described as "a string consisting of a million zeros," which is quite simple. On the other hand, as illustrated by the popular kids game "Twenty Questions," the answers given to 20 questions in a series, assuming the answers to the question discriminate between equally probable alternatives, can distinguish between more than a million possible answers (another way of saying this is if I ask you to think of a number between 1 and a million, and I ask the question, "Is it higher or lower than (a certain number)," I could guess the number correctly after only 20 guesses. A bit string consisting of 110110110110110 repeated a million times could be reproduced by a short message that is not very complex, even though the message is long. If the string has random 0's and 1's, however, it cannot be compressed into a short message and is therefore considered complex. Using this logic, Gell-Mann defines effective complexity of a system as "roughly characterized as the length of a concise description of the regularities of that system or string" (Gell-Mann, 1994, p. 50).

Using this as a definition, all living organisms are quite complex, if you are using their DNA as a measure to describe them. Even a simple bacterium such as E. coli has DNA with a string of five million nucleotides. The possible combinations of different strings even for this so-called primitive organism is a 1 followed by 600 digits (Gell-Mann, 1994). "Even a single mutation can have a significant effect on cell behavior. For example, the mutation of a certain gene in an E. coli cell to a certain new allele could, in principle, lead to the resistance of that cell to a drug such as penicillin" (Gell-Mann, 1994, p. 67).

PROPERTIES OF COMPLEX ADAPTIVE SYSTEMS

Holland (1995) writes of four basic properties and three mechanisms common to all CAS:

1. **Aggregation.** Individual agents aggregate and act as a single entity. For example, a human brain consists of perhaps 10 billion brain cells, without any single brain cell being "in charge." In the aggregate, the brain acts in a much different way than any of its constituent neurons. In the context of public administration, the Congress has "properties" that are unlike the individual members of Congress. A common example from the literature is that most constituents are pleased with their member of Congress, but have a low regard for the institution (Fenno, 1978). Organizations consist of individuals, and may develop a character that is not entirely consistent with the character of the individuals. The Congress has a "property" to delay enactment of legislation, referred to in the literature as "assembly coherence" (Mayhew, 1974), even while the

individual "agents" are all screaming for quick action on an issue and blaming the institutional structure.

2. **Tagging.** This describes how agents differentiate in a way that fosters aggregation and transmits information. As an example, the spin of a totally white cue ball cannot be distinguished because of its perfect symmetry. But if we put a stripe around its equator, we can determine how it is spinning. CAS tend to have these tags to impart more information than would otherwise be the case (such as the trademarks and logos that impart more information about the organization that produced a product one might buy). National flags and military uniforms may be an example of tagging in the public administration context.

3. **Nonlinearity.** This means that you can't necessarily get a value of the whole by summing its parts. A simple example of a nonlinear equation is to calculate the population of a predator and its prey. Rather than a direct or inverse relationship between predator and prey, the mathematics show that both populations will go through an oscillation between feast and famine. In the organizational setting, doubling inputs may not necessarily double output (and, in some cases, can decrease output). CAS also possess "lever points" in which small changes produce large outcomes. A recent example of a "small" change that produced a large outcome in the context of public administration is the policy of the Florida Secretary of State in deciding what to do with certain disputed ballots during the 2000 Presidential election.

4. **Flows**. CAS show properties of flows, among them the multiplier effect and the recycling effect. Both of these effects are seen in economic systems, which are an aggregation of billions, if not trillions, of individual transactions annually.

A dollar circulated in the economy is an illustration of the multiplier effect. The dollar spent by person A goes to person B in exchange for goods or services. Person B spends a part of the dollar and saves some. The fraction spent by person B is received by person C, who spends part of it and saves some, and so on. The net result is that spending a dollar results in economic activity of much greater than $1.

While the total amount of nutrients in a rain forest is relatively small, the effect of plants dying and having their nutrients reused is enormous—an illustration of the recycling effect.

5. **Diversity**. Adaptations that fill empty niches are encouraged by the "learning" of CAS, which creates diversity of structure. In the organization context, many organizations that have a similar purpose seek out a niche to have a survivability advantage, filling a so-called "fitness landscape."

6. **Prediction.** CAS engage in "prediction." For example, even lower level organisms move toward a chemical gradient, predicting that its movement will be rewarded with food. The system, overtly or otherwise, creates a model of all possible behaviors, and moves toward the one that increases its chance of survival (or it doesn't survive). For example, a political action committee (another form of CAS) predicts that making a contribution to a member of Congress will influence his/her vote. Empirical research indicates that there is such a correlation, in certain cases, between the amount of the contribution and the probability of influencing a vote (Haider-Markel, 1999).

7. **Use of generic building blocks.** CAS use generic building blocks to create specific complex structures. Quarks come together to create nucleons. Nucleons come together to create atoms. Atoms come together to create molecules. Molecules come together to create cell walls and cells. Cells come together to create organs. Organs come together to create an individual. Individuals come

together to create organizations. Organizations come together to create associations. Because each of the agents forming the CAS interact with each other, the properties of the CAS are likely to be quite different from the properties of the individual agents.

Anderson (1999) sets out six properties of complex systems that he claims "should be regarded as well-established scientifically" (examples are my own):

1. Many dynamical systems (defined as systems whose state at any given point in time determines its state at a future point in time) do not reach either a fixed point or a cyclical equilibrium.

For example, the number of applications to a Ph.D. program in Public Administration can't be predicted with any certainty, and fluctuates with apparent randomness, without having either a repeating pattern (e.g., four applications in year t, six applications in year $t+1$, eight applications in year $t+2$, or any progression that could be described by a function, or a pattern that approaches some limit as t approaches infinity).

2. Apparently random processes may actually be chaotic, i.e. they revolve around fractal objects that constrain the system within a boundary, but which never repeat in any finite period of time.

Like the stock market, the number of Ph.D. applications is likely to fluctuate around a boundary such that the number is likely to be between five and 25. The boundary, however, is likely to be influenced by many factors, such as the cost of tuition, the availability of scholarships, the reputation of the program, and the general economy.

3. These systems display sensitivity to initial conditions. For example, the retirement of a popular professor could theoretically have a dramatic effect on the number of Ph.D.

students that apply for and successfully complete the program over the next ten years.

4. These systems do not respond well to reductionist analysis; i.e., the whole is often more than the sum of its parts because of interconnections and feedback loops involve all of the subsystems concurrently. For example, trying to identify the bottleneck in what is causing Ph.D. program participants to leave the program, such as one professor who is being too tough on students, and removing that bottleneck will not necessarily result in the program becoming more effective, because that professor is also likely to contribute some positives. Removing that professor will entirely change the system to a different system, and such removal may create a different bottleneck.

5. Simple rules or equations governing these systems can create complex patterns. These patterns grow more complex the higher up in a hierarchy the level of analysis is taken (e.g. a cell, an organ, an individual, a family, a neighborhood, a city, a county, a world). For example, simple rules involved in analyzing decisions made in a Ph.D. program are that Ph.D. students, faculty, and administrators maximize their utility and also make decisions designed to increase their survival in the program. However, the interactions among all of the players and task environment show turbulence, if not hyperturbulence. Some subsystems don't survive (e.g. students leave the program), and faculty make collective decisions in committees (a type of CAS) that may not be in the program's best interests or even their own personal interest, simply because of the unique group dynamics that occur at any particular meeting.

6. Complex systems often start in a random state and emerge and evolve toward a state of order, exhibiting "self-organizing" behavior (and in a thermodynamic context, import energy to accomplish this). An example might be the Ph.D. program's Doctoral Students Association, which may

have started out as a random idea of minimal self-organization. Complexity theory suggests that the student members could create a beneficial complex adaptive system (CAS) that would increase the probability of all of its members to survive, by engaging in cooperative behavior. In this context, it might be by organizing into something more resembling a union than a social club, or having a centralized web site to post information of use to all of the members (such as term papers, preliminary exam papers, past comprehensive exam questions, reviews of books, and a place to exchange information about professors, courses, jobs, and fellowships).

COMPLEXITY AND ORGANIZATIONS

According to Anderson (1999), there are four elements that characterize complex adaptive systems in the context of organization theory. He writes that "The hallmark of this perspective is the notion that at any level of analysis, order is an emergent property of individual interactions at a lower level of aggregation" (Anderson, 1999, p. 219). These elements are:

1. The outcome at any particular level of analysis is produced by a dynamic system comprised of agents at a lower level of aggregation. For example, the outcome of the Ph.D. program system consists of the interactions of the agents at the lower level of aggregation that, in this case, is the group of students, faculty, staff, and administrators. The agents act individually based on their individual skema, the cognitive structure that determines how the individual actor will behave based on its perception of the environment.

2. All of the agents are interconnected by feedback loops, and the behavior of each agent is determined by information it receives from the other agents to which it is connected. This means that there is no central control directing the behavior of all of the agents of a system, but rather the agents individually self-organize. Obviously, the coordinator of the Ph.D. program does not centrally control the behavior of the agents (such as the students), or they would all stay in the program, pay their tuition, complete all of their reading assignments, and attend every class. There is constant communication among the agents; and the interaction of a class is likely to be entirely different when one "agent" decides not to attend that class.

3. There is a symbiotic relationship among the agents, such that each agent adapts to the environment and cooperates with other agents to increase its chances of survival. The probability of future survival of each agent is dependent on the choices made by all of the other agents. While an equilibrium can be created from this so-called "co-evolution," small changes in behavior by one agent can produce small, medium, or large changes in outcome for the system. Thus, rather than seeing other students as competitors, an enlightened Ph.D. student using the complex adaptive system model will see that the dropping out of one student from the program does not mean that there will be more resources for all of the other students (i.e., a positive outcome that might be predicted by analyzing the situation using traditional models) but will rather see that this loss may make it less likely for the entire program to remain viable.

4. The system adapts and evolves through time as a result of the entry of new agents, the exit of existing agents, and the changes in behavior of agents. The factors that make some agents more successful than other agents can be learned by the other agents (i.e., their behavior adapts), and the outcomes for the system change, the interactions and connections among the agents can become stronger, and new complex adaptive systems can form within the existing complex adaptive system (e.g. an organism might develop an immune system, or a Ph.D. program might organize a union of its students to change the power relationship between the administration and the students).

ENERGY, ENTROPY, AND ORGANIZATIONS

Entropy is the measure of disorder, and is constantly increasing in a closed system, consistent with the Second Law of Thermodynamics. Complexity appears at first to contradict this law, but the fact is that just as there is no perpetual motion machine (you can always identify a source of energy that is driving the machine), these systems that are increasing their order and complexity are always importing energy. The Second Law applies to closed systems as a whole (such as the universe), but doesn't apply to open systems that can import energy and form "dissipative structures" that resist equifinality. Self-organization can only occur in open systems that have the ability to import energy (Prigogine and Stengers, 1984). Anderson (1999, p.222) suggests that the more turbulent the environment for an organization, the more energy must be imported to sustain the self-organization. In the context of public organizations, "energy" is likely to mean new ways of doing business processes, new workers, increased appropriations from the Congress or state legislature, and innovation.

THE EDGE OF CHAOS

Complexity theory suggests that there is a quasi-equilibrium state, just short of the point where a system would collapse into chaos, at which the system maximizes its complexity and adaptability. This point is referred to in the literature as "the edge of chaos." The term "edge of chaos" was coined by Chris Langton to describe the fact that complexity resulted from physical phenomena interacting just short of becoming chaotic (Waldrop, 1992, p. 230).

Critical values of certain variables often place a system at the edge of chaos, where it is usually found sandwiched in between complete stability and complete chaos. Complexity theorists such as Langton suspected that this phenomenon is analogous to what happens in second-order phase transitions such as the transition between ice and liquid water, and liquid water and steam (Waldrop, 1992). Kauffman (1995) suggests that all CAS evolve "to the edge of chaos," which he describes as close to the boundary between order and disorder. "It is a very attractive hypothesis that natural selection achieves genetic regulatory networks that lie near the edge of chaos" (Kauffman, 1995, p. 26). Many complexity theorists who study organizations use this metaphor as well (see below). Kauffman uses "the edge of chaos" notion to describe all innovative CAS, including one novel application to democracy:

> "The edge of chaos may even provide a deep new understanding of the logic of democracy...we will find surprising new grounds for the secular wisdom of democracy in its capacity to solve extremely hard problems characterized by intertwining webs of conflicting interests. People organize into communities, each of which acts for its own benefit, jockeying to seek compromises among conflicting interests. This seemingly haphazard process also shows an ordered regime where poor compromises are found quickly, a chaotic regime where no compromise is ever settled on, and a phase transition where

> compromises are achieved, but not quickly. The best compromises appear to occur at the phase transition between order and chaos…Democracy may be far and away the best process to solve complex problems of a complex evolving society, to find the peaks on the coevolutionary landscape where, on average, all have a chance to prosper" (Kauffman, 1995, p. 28).

The edge of chaos is also the point where small changes in a system produce cascades of change consistent with a power law. A power law is a mathematical relationship that predicts that a small change can affect a system in a small way or a large way, such that the probability of the amount of change is inversely proportional to the size of the change. In practical terms, this means that a large change (of, arbitrarily magnitude 10) has a 1/10 chance of occurring compared to a small change of magnitude 1. This law is illustrated in nature by performing a classic experiment first conceived by physicist Per Bak in which a grain of sand is dropped continually upon a pile. When a critical point is reached, a grain of sand will trigger either small landslides or even large avalanches with a frequency approximating 1/x where x is the size of the avalanche (Kauffman, 1995, p. 28).

The power law is also known as the 1/f law. One often takes for granted that most natural phenomena are distributed consistent with the normal distribution but, in fact, another distribution more aptly describes them in situations labeled as "self-organized criticality" (SOC).

Self-Organized Criticality (SOC) is viewed as "a phenomena of sudden change in physical systems in which they evolve naturally to a critical state at which abrupt changes can occur. That is, when these systems are not in a critical state, i.e., they are characterized by instability, output follows from input in a linear fashion, but when in the critical state, systems characterized by self-organized criticality act like nonlinear amplifiers, similar to but not as extreme as the exponential increase in chaos due to sensitive dependence on initial conditions. That is, the nonlinear amplification in a self-organized, critical system follows a power law instead of an exponential law. SOC systems are self-organized in the sense that they reach a critical state on their own. Examples of such systems include avalanches, plate tectonics leading to earthquakes or stock market systems leading to crashes. Because SOC systems follow power laws, and because fractals also show a similar mathematical pattern, then it may be the case that many naturally occurring fractals, such as tree growth, the structure of the lungs, and so on, may be generated by some form of self-organized criticality" (Lindberg, 1999).

Kaufman suggests that evolving to the edge of chaos gives the CAS a selective survival advantage, compared to outcome systems that are not at the edge of chaos. He theorizes that it is through the large avalanches, not the small cascades, which result in evolutionary change that survives (which is a direct contradiction of the conventional wisdom that biological evolution resulted from the aggregation of small changes over billions of years). Perhaps this model can be applied to public organization lifecycles and other phenomena as well (2).

The "edge of chaos" is a useful construct to explain some of the apparent paradoxes of management. One of the paradoxes of management or organizations is that stability and flexibility are both seen as creating organizational effectiveness, even though these two constructs are opposites. Chaos and complexity theories reconcile this. Using this concept in the organizational context, organizations that are too stable fail to respond to changing conditions in the environment, are at a competitive disadvantage, and eventually go belly-up. Organizations that are changing too much also disintegrate. Yet there is an optimal place between these two that promotes survival, the edge of chaos, where the organization is the most creative, promotes the most learning and adaptation and, as paraphrased by Ralph Stacey, get to the future before your competitors do (Stacey, 1996). Stacey writes that complex adaptive systems, including organizations, learn and be creative "only when they operate at the edge of system disintegration. That place at the edge of disintegration is a kind of phase transition between a stable zone of operation and an unstable or disordered regime" (Stacey, 1996, p. 9). He sees an analogy with the idea that there is not much difference between those who are geniuses and those who are mentally ill, and theorizes that this is simply an extension of a natural physical law rather than a coincidence.

As Matthews, et al. (1999) state, "The system must not exhibit too much order as to fall into the 'trap' of inertia and stasis, but must also guard against the extremes of disorder and chaos" (p. 6).

LESSONS OF THIS THEORY FOR ORGANIZATIONS

The traditional view of management is that the manager sees something that has not gone according to plan, and tries to fix it by "troubleshooting," trying to find the piece that "broke" and fix it. "The study of complex adaptive systems suggests that we might be better off maintaining the anxiety, sustaining the diversity, letting the thing simmer for a while longer to see what will happen on its own" (Plsek, Lindberg and Zimmerman, 1997, p. 3).

For the manager, this creates a dilemma, even in the self-organizing environment. If one does not place sufficient constraints and "control" workers, they may reach a point where the organization goes unstable. Yet too much control limits adaptability.

> Those running an organization, if they want maximum learning and growth, have a very fine line to tread to maintain this. If there is too much change and freedom, then their system can tip over into chaos—witness what happens in a revolution, for example. Too little innovation, and systems become rigid—totally predictable but able to respond only through tried and established methods. Governing an organization is therefore an art, and there needs to be constant monitoring of the system to check which way it is heading. If it is becoming too stable, then change and a degree of freedom, perhaps through decentralization, needs to be introduced to push the system back to complexity. Conversely, if there is too much change and the system is threatening to melt down, restraints and disciplines must be quickly reinforced (Lewis, 1994, p. 16).

Lewis uses communication policy to give an organizational example of how complexity theory can be applied. He notes that some have suggested that the purpose of an organization is to reduce and block communication so things can get done rather than talked about. An organization that has no rules concerning communication will have "total chaos and breakdown," because every worker will be overwhelmed with memos, meetings, and telephone calls. Yet placing restrictions on communications (such as between departments) provides control and stability, yet "little learning or change." Good managers and organization leaders know when to change communications rules to move the organization to the edge of chaos (either away from chaos or away from stability) in order to promote organizational learning.

Lewis suggests that top-down change designed to make an organization more effective and flexible is doomed to failure, because of the impossibility of predicting the outcome of any change. He points out that major change is usually the result of "a mutant subculture which spreads within the organization" and takes over because, to paraphrase him, it is better able to adjust to the outside environment it deals with.

Describing the edge of chaos, Frederick (1998) writes—

> Corporate life is a never-ending push-pull kind of existence. Technological innovations, eagerly sought by inside wizards or fearsomely thrust forward by outside competitors, push the corporation ever onward in new ways of doing things. The best companies invite and accept this kind of challenge. However, recall the risk run by an CAS—it may change so rapidly and its new technologies may inject so much novelty and turbulence into normal operations that the entire system risks plunging over the EOC (Edge of Chaos). The pressures for change are unrelenting...(p. 373).

Plsek, Lindberg and Zimmerman (1999) offer nine management principles that conflict with the traditional management approach, but which take advantage of the insights provided by complexity science. In summary, they are to view your organization as a complex system rather than using the machine metaphor; provide minimum specifications, and don't script plans in minute detail; don't always "go with the data" when "going with your gut" feelings may be more appropriate; take your organization to the "edge of chaos" by fostering a level of anxiety, diversity, discomfort, and contentiousness to promote creativity; take advantage of paradox and tension rather than fighting them; let solutions to knotty problems emerge; promote informal communication networks in the organization rather than banishing them; and use the "tit-for-tat" strategy of competition-cooperation to forge positive, symbiotic relationships as a first strategy and abandon that as a strategy only when your "partner" does not reciprocate.

More practical suggestions are provided by group members of VNA, Inc., (Anonymous, 1999) who consist of both practitioners and academics on the cutting edge of complexity applications, mostly in the healthcare field. Among the techniques they feel contribute to constructive emergence are the following:

1. Increase the flow of information in the system.
2. Use fundamental questioning to keep organizational members thinking about solutions to organizational problems
3. Keep the size of work teams to 12 or less, and organizational units to 150 or less, to be consistent with the number of relationships people can handle.
4. See the manager as a participant and part of the work system, rather than as an outsider.
5. Promote redundancy, and fight against the traditional practice of guarding information and skills to ensure longevity or security.
6. Don't be afraid of letting unstable situations simmer until a solution emerges rather than forcing a solution.

7. Consider doing large group interventions where the people put in a room to solve a problem are not just organizational leaders, but a cross-section of organizational members.

CONCLUSION

Organizational theory has shamelessly borrowed from the physical and biological sciences for its models and metaphors. These models and metaphors have been unsatisfactory in predicting the behavior of organizations, and to provide prescriptive designs for creating organizations that are more efficient and effective.

Complexity theory is a new way of looking at how complex structures form, adapt, and change. While it appears to have clear applicability to explaining natural phenomena such as the formation and properties of molecules and the creation of biological systems, it remains to be seen whether it can be successfully applied to organizations. While the literature is filled with calls for changing the paradigm of organization management from one of control to one of self-organizing, there is a paucity of empirical data confirming that organizations designed on this new model are more effective and efficient. There is a view that putting aside whether this results in more efficiency and effectiveness, self-design is more in line with emerging philosophical and ethical views about the workplace. In a normative sense, a complexity theory view can be considered more humanitarian and ethical. Writers in the field, in addition, suggest that organizational designs based on this new paradigm are likely to be more efficient and effective in turbulent environments.

As more and more large organizations change their organizational design model to follow the prescriptions of complexity theorists, there will be more opportunities to judge whether these new designs work. This suggests a research agenda that uses the scientific method to determine whether the principles advocated by complexity theorists in the organizational arena can truly improve organizational performance. Until that evidence is available, however, complexity theory remains useful to describe the adaptation process of organizations, and offers lessons to explain how organizations can take advantage about what we know about biological systems.

NOTES

(1) A paradox is seen as "an idea involving two opposing thoughts or propositions which, however contradictory, are equally necessary to convey a more imposing, illuminating, life-related or provocative insight into truth than either factor can muster in its own right..." (Slaatte, 1968, in Cameron, 1986).

(2) In 2001, after reading Per Bak's fascinating book *How Nature Works: The Science of Self-Organized Criticality*, I became excited about applications of his theory in public administration settings. I looked for 1/f law behavior in the magnitude of line items in the Commonwealth of Pennsylvania's FY 2000-2001 state budget and the number of pages of Acts enacted by the General Assembly the previous two years. In neither case did I see evidence that the distribution followed a power law.

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