III

Interdisciplinary Philosophies and Theories

Chapter 6

Complexity Science and Complex Adaptive Systems

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INTRODUCTION

Complexity science (CS) is an emerging paradigm that is being integrated into the healthcare literature as a new approach from which to view clinical care and healthcare organizations (HCOs). Grounded in physics and mathematics, it offers a fresh approach for studying regularities that differ from traditional science. Unlike traditional science that incorporates laws of science, CS is based on the notion that complexity emerges from simple rules (Phelan, 2001).

The theoretical concepts of complexity have been broadened into a paradigm of science concerned with the interconnection between individual units or agents (Kauffman, 1995; Waldrop, 1992). CS has expanded recently to include the ability to analyze huge amounts of data through computers. Thus, it has expanded the view of scientific research beyond purely linear reductionism. CS has been applied to fields such as weather forecasting, economics, and the neurosciences as well as social and organizational behavior. The term *complex adaptive system* (CAS) refers to a special application of complexity that bears some similarity to systems theory. As such, this framework will likely have an inherent resonance with nurses. The idea of nested systems from the individual patient, family, and community—as well as the healthcare unit, organization, and healthcare system—is familiar to most nurses. CASs have recently been applied to health care in relation to physiology and medicine. Additionally, complexity frameworks have been applied to local healthcare systems (Anderson, Issel, & McDaniel, 2003; Crabtree, Miller, & Strange, 2001) and organizations.

Biomedical scientific frameworks of mechanism and reductionism, which have produced excellent medical advances, have not always been a good fit for nursing. This lack of fit

Table 6-1 Complexity Science Terminology

Complexity science: The science based in physics and mathematics that uses basic principles such as simple rules or functions to explain the relationship between variables, and that allows for variations and emergent behaviors that are not fully predictable. Computer modeling using these rules/functions has accommodated large amounts of data that allow for the study of phenomena on intermediate levels in dynamic systems.

Nonlinear dynamics: The mathematics used to understand complex deterministic systems with complex behavior.

Complexity theories or concepts: The basic principles or concepts from complexity science and complex adaptive systems that are *applied,* often metaphorically, to other biological and social systems.

Complex adaptive systems (CASs): The application of complexity theories and systems perspectives to living, dynamic systems in biology and other systems.

Complex responsive processes (CRPs): The application of complexity to organizations in which a CAS is not completely applicable based on organizational structure and the ways in which people learn and form mental models in structured organizations. Currently, new mathematical models are being applied to science at all levels and the language has begun to penetrate other areas.

has led to a long-standing problem for nursing professionals when they try to ground practice, research, and scholarship in reductive scientific approaches. In reality, many nursing activities could be better understood through a complex, dynamic systems framework. Therefore, it is important for nurses to understand this movement and become familiar with its basic concepts and principles (see **Table 6-1** for definitions). A word of caution is offered; the vocabulary that supports CS is often confusing, and the concepts sometimes seem to be inconsistent.

The purpose of this chapter is threefold: (1) to introduce the reader to the roots, common terminology, and basic concepts of CS and math, which serve as a foundation for understanding their application to nursing, health care, and HCOs; (2) to explore the CAS, a special form of complexity particularly relevant for nurses; and (3) to discuss the implications of CS for practice and health care.

INTRODUCTION TO COMPLEXITY SCIENCE

CS is not a single theory but rather an emerging field of science that is engaging scholars and scientists in a new paradigm of interdisciplinary study. Complexity, CS, and the CAS are being described in a number of fields, including physics, mathematics, biology, economics, and the biological and social sciences. CS is attracting a diverse group of scholars and scientists across disciplines to view phenomena of interest through a new lens. Many scholars have identified it as a new paradigm in science. A prominent physicist has stated recently that complexity is a technical scientific revolution that will change the focus of research in all scientific disciplines, including human biology and medicine (Baranger, 2009).

For the past century, science has been focused largely on an analytical/reductionist paradigm of breaking things down into smaller units and isolating the parts from their contexts in an effort to understand how these parts operate in nature. The reductionist approach has been very successful in many ways and has engendered tremendous progress in health-related fields. Nevertheless, this approach is not sufficient to understand nature, especially living entities that are dynamic and adaptive. This limitation has been a concern in the nursing profession, which is oriented to a more holistic approach.

Several scientists from the physical and biological sciences have postulated that CS will be the preeminent science of the 21st century (Baranger, 2009). Robert Laughlin, Nobel laureate and physicist, has been quoted as stating that science has shifted from the *age of reductionism* to the *age of emergentism* (as cited in Kelso & Engstrom, 2006). This trend represents a fundamental shift away from breaking things down into the smallest parts and toward supplementing this approach with understanding of the behavior of the whole.

This paradigm shift is echoed by Sturmberg and Martin's (2009) speculation that the unilateral focus on reductionist thinking has resulted in some of the problems that we now face in health care. These authors call for the application of complexity systems thinking to address the social dimensions of health care. Their call is not to abandon the reductionist view, but rather to embrace both the holistic and reductionist perspectives to gain a new and more complete understanding of the world. This shift toward examining the whole, as well as appreciating the component parts and their relationship, combines the two views as a "both/and" perspective rather than an "either/or" approach in CS.

While CS is not a unified theory, its constructs have been applied to health care, and many of the general principles and concepts have an inherent resonance with nursing. The perspective of seeing the whole, which is perceived as more than the sum of its parts, is fundamental to nursing theory; therefore, this perspective is an important opportunity for nurses to understand the CS movement and become familiar with its key concepts and principles. As noted previously, the vocabulary that supports CS is often confusing, and the concepts are defined inconsistently.

CS has been applied to a number of fields such as computing, economics, and earth sciences. Aspects such as agent-based modeling and computer simulations have recently been applied to health care in relation to physiology and medicine. Complexity frameworks have also been applied to local healthcare systems, social behavior, and organizations. These latter applications have significant relevance to nursing because many nursing theorists have a systems theory orientation. While notable debate has ensued about the relationship between complexity and systems theory, especially in relation to some of the more recent advancements proposed by Richardson (2005), many authors point out that CS has many of the same elements of systems theory, which is a theory very familiar to nursing. The systems orientation situates patients, families, and organizations within hierarchies of systems. With these systems orientations and theoretical frameworks, the biomedical scientific framework of mechanism and reductionism has resulted in a less precise fit for nursing than was previously thought. The lack of fit has produced a long-standing problem for nursing researchers who try to ground practice, research, and scholarship in reductive scientific mechanisms. It is apparent that many nursing activities could be understood better through complex dynamic systems frameworks.

BACKGROUND

It may be helpful to differentiate between CS as the application of mathematical and physics science to large data sets and the use of computer modeling. CASs are special cases of complexity in which some of the basic constructs are used and generally thought of more as complexity theory or a conceptual framework. CS is grounded in theoretical mathematics and physics and is concerned with the interconnection between agents (Kauffman, 1995; Waldrop, 1992). Agents are units or components of the system; they may consist of individual people, birds in a flock, bees in a hive, or a component of a human system such as genes or neurons. An example is the heart and circulatory system, both of which act as agents within a body.

Many of the complexity concepts come from chaos theory, quantum mechanics, and nonlinear mathematics. It is the interconnection between or among these agents that is the focus of CS. *Chaos theory* signifies a different concept from the common usage of the term chaos. In a chaotic system that conforms to chaos theory, behaviors may appear to be chaotic, random, or incoherent when analyzed in a linear fashion; in contrast, when analyzed using nonlinear approaches, the system exhibits dynamic *patterned* variation. For this reason, chaos theory is described as patterned complexity rather than being equivalent to the common usage of the terms chaos and random incoherence.

CS provides language, metaphors, conceptual frameworks, models, and theories that can be applied to health care. A *metaphor* is a figure of speech in which a word or phrase literally denotes one kind of object or idea in place of another to suggest a likeness or analogy between them. Metaphors are useful in describing complicated concepts because they provide a good conceptual analogy, allowing us to communicate and think about abstract concepts. For example, the metaphor of a machine is used to convey the idea of parts that can be identified and understood. This metaphor has been successfully applied to understanding the mechanisms of how things behave or operate.

The use of metaphors in CS also can help communicate abstract information. These metaphors shape our thinking and perspective by connecting an idea to a known concrete entity. In one sense, then, all scientific thinking is metaphorical because the metaphors influence which questions we ask and how we understand phenomena. The machine metaphor has been the predominant metaphor shaping our thinking about physiology and guiding medical research. Indeed, a large amount of medical research is devoted to understanding the mechanisms, whether they are at the genetic, biochemical, structural, or physiological levels. For example, clinical practice and research trials are predicated on understanding the mechanism of a disease or disorder, developing an intervention to repair function, or interrupting a disease process. The expected outcome is better function or a reduction in signs or symptoms of the disease. This linear process approach is a dominating factor in terms of the way we think about clinical research and patient care, with the outcomes being based on efficacy and efficiency.

The machine metaphor not only has been used to make sense of physiological functions of the body, but it has also been applied to social organizations. Although useful, this metaphor has limitations for understanding individual behavior and organizations. CS, by comparison, provides a different metaphor that looks at living systems as complex, adaptive, self-organizing systems. CS is concerned with the relationship among the units, components, or agents rather than just the components themselves. This perspective sheds light on how individuals and organizations behave and how change happens (Zimmerman, Lindberg, & Plsek, 1998). Physicists have identified laws of quantum mechanics on the micro (atomic and subatomic) and cosmic levels, which have been metaphorically applied at the intermediate levels (i.e., the behavior between the atomic and cosmic levels). Currently, new mathematical models are being applied to science at all levels, and the language has begun to penetrate other areas, including health care. Adding this perspective of understanding is most relevant to health care and to the profession of nursing.

Many healthcare disciplines are beginning to acknowledge the limitations of using only reductive approaches and the machine metaphor (Plsek & Greenhalgh, 2001; Sturmberg & Martin, 2009). Consider an example from the field of genetics. Researchers who identified human genes inspired new questions about how these genes are activated. Genetic researchers have become aware of the importance of understanding the gene and its molecular aspects (micro level) as well as the context, the environment, and the ecosystem of behavior (macro level) influencing gene behaviors. Elucidation of both levels is necessary for understanding how genes behave in a human organism related to expressions of health and disease. As noted previously, scholars are not suggesting that CS wholly replace analytical reductive science; rather, CS embraces both the reductive and the complexity perspectives (Lindberg, Nash, & Lindberg, 2008). Using this approach in nursing allows us to begin to address the complex challenges of patient behaviors, work environments, and care environments.

THE SCIENTIFIC ROOTS OF COMPLEXITY SCIENCE

A brief introduction to the mathematical and scientific roots of CS grounds the understanding of the concepts, which are applicable to other systems such as individuals, groups, and organizations. The following descriptions of nonlinearity are adapted from Liebovitz's

(1998) explanations of fractals and chaos, with the concepts being simplified here for the life sciences. Another scientific application of CS lies in coordination dynamics where mathematics is applied to reconcile the polarized world of contradictory pairs for the purpose of understanding the poles and the world between them.

Nonlinear Mathematics

Nonlinear mathematics provides a language to explain complex dynamic changes over time and three-dimensional space (four dimensions); it focuses on the interactions among variables, rather than the variables themselves. Some of the major concepts are presented in this section, although a full discussion of the mathematical and science concepts is beyond the scope of this chapter. Nonlinear approaches can be applied when the data do not follow a normal distribution pattern or when additional data do not fall close to the norm. Given that these concepts apply to the mathematical functions and patterns, one must be careful when applying them directly to other observed phenomena. **Table 6-2** lists some nonlinear dynamics concepts.

Focus on Simple Rules

These mathematical functions refer to the rule that describes relationships. For example, in the common equation $1 + 1 = 2$, a linear approach deductively examines the dependent variable as 2 and then focuses on the two independent variables of 1. In contrast, the nonlinear approach focuses on the plus (+) symbol, which is the rule or mathematical function that explains the relationship between the variables.

Coupling

Coupling examines the strength of the relationship between functional units. Additionally, the whole may be greater than the sum of the parts.

Table 6-2 Nonlinear Dynamics Concepts

- Nonlinearity
- Focus on simple rules
- Coupling
- Deterministic
- Sensitivity to initial conditions
- Fractals and self-similarity
- Scaling
- Emergence

Deterministic Systems

In a *deterministic system*, system behavior is not random, but rather has coherence or a pattern. A small number of equations and the understanding of their variables from the past can be used to compute values in the short term. Computer modeling may be used to make these explanatory predictions. The simple rules/functions specify how these variables change over time and space, at least in the short run.

Sensitivity to Initial Conditions and Perturbations

An *initial condition* is the starting point of a dynamic system, and a small difference in starting values can result in significantly different trajectories. To understand this concept, picture a plot on a graph where a minuscule difference in the starting point could alter the angle of the trajectory so that it points in a different direction if you tracked it over time. These perturbations can disrupt a system or create new emergent behaviors.

Fractals and Self-Similarity

A *fractal* is a geometrical pattern or structure that is self-similar and repeating. Similar patterns are repeated on different scales or resolutions. The similarity may be apparent, but when used strictly in mathematics and science, it is also mathematically similar so that the scales are proportional (i.e., self-similar). A common classic example from the discovery of fractal geometry is provided by Mandelbrot (1967, 1982). He described the coastline of England as a fractal because as it is observed from closer points of view (i.e., by changing the scale of magnification), the patterns appear to be repeated in a self-similar pattern. If you were to use binoculars and take repeatedly closer looks (different scales of resolution) at the entire coastline, you would likely see similar patterns, albeit on an even smaller scale. In CS, one finds self-similar mathematical patterns.

Scaling

The different resolutions of measurement are referred to as *scaling*. Perhaps more familiar examples of fractals would be the body's networks of blood vessels or the branches of a tree, in which the patterns are repeated on different scales; in other words, patterns are repeated at increasingly finer and finer resolution. In CS, new information is apparent at finer resolutions. As the object is viewed under continually closer resolutions, the object appears more complex rather than exactly the same. Liebovitz (1998) distinguished non-fractal objects from fractal objects when he stated, "As a non-fractal object is magnified, no new features are revealed. As a fractal object is magnified, ever finer features are revealed. The shapes of the smaller features are kind of like the shapes of the larger features" (p. 4).

Emergence and Coordination Dynamics

The unpredictability of a complex system that allows for new and unexpected behavior that is generated by the system itself is called *emergence*. Another scientific application of complexity lies in *coordination dynamics*—the study of patterns of coordinated behavior in living things.

In addressing coordination dynamics, Kelso and Engstrom (2006) noted, "It is a set of context dependent laws or rules that describe, explain, and predict how patterns of coordination form, adapt, persist and change in natural systems" (p. 90). These dynamics exist between two points or between complementary pairs. In their book *The Complementary Nature*, Kelso and Engstrom explored many of the contraries or oppositional pairs that are ubiquitous in the way humans make sense of the world. Coordination dynamics are a way to begin to understand these dichotomies, dualities, and polar opposites.

Complementary Pairs

By definition, complementary pairs are opposed; they actually are coexistent, linked, and often mutually dependent. Kelso and Engstrom (2006) recommended that these dichotomized pairs be written with the tilde symbol (~)—for example, mind~body, random~determined, objective~subjective, local~global, stability~instability, and qualitative~quantitative. In approaching complementary pairs, it is important to understand not only both poles of the pairs, but also the dynamics that occur between them. A scientific example is the wave~particle theory of light. The dynamics of waves and particles, as well as the interaction between them, are needed to describe light comprehensively.

Coordination dynamics offers a way to address the whole~part phenomena. Using coordination dynamics harkens back to the appeal to think in terms of "both/and" rather than "either/or" or "black/white." Likewise, the study of living things can be studied by reductive/analytical~emergent approaches. One key feature of coordination dynamics is control parameters, which can be either endogenous or exogenous. Control parameters can cause the system to adapt and change; conversely, they can be stabilizing to the system. Thus, the control parameters may be described as stabilizing~destabilizing/transformative. Life is replete with ambiguities and paradoxes.

COMPLEX ADAPTIVE SYSTEMS

The term *complex adaptive system* (CAS) refers to special cases of complex systems. CASs have been studied for more than 40 years, beginning at the Santa Fe Institute, where interdisciplinary researchers investigated the application of CS in physical, biological, computational, and social sciences. Other groups across the world also have engaged in the application of CS and CASs to real-world problems. The control within a CAS is decentralized and dispersed. Coherent behavior in the system arises from competition and cooperation among the agents (Waldrop, 1992). A CAS is a collection of individual agents with freedom to act in ways that are not always totally predictable and whose actions are interconnected so that the action of one part changes the context for other agents (Wilson, Holt, & Greenhalgh, 2001).

A CAS is a network consisting of many agents that follow simple rules, are in constant dynamic interaction with one another, and can generate complex structures. The CAS has the capacity to adapt and become a good fit within a changing environment. This ability to adapt allows the organism or organization to continually modify itself relative to a changing environment by changing the rules of interaction among component agents. The process of adaptation occurs through learning new rules or behaviors and accumulating new experiences. In this process, the organism/organization evolves through a process of self-organization, which in turn, allows for creativity and lacks complete predictability. A cardinal aspect of a CAS is that small actions or inputs may have large effects; conversely, large inputs may have small effects.

A CAS has a high degree of adaptive capacity and is characterized by self-similarity, complexity, emergence, and self-organization. The concept of CASs has been used to describe a flock of birds, a school of fish, a hive of bees, a human body, a family, and a community in which each level is considered a system that is different from, and more than, the sum of its parts of components. Each of these CASs is embedded in larger contexts. Moreover, CAS concepts have been applied to human physiology, such as cellular networks, neural networks, and body systems such as the cardiovascular system. It is clear that the application of a CAS perspective is broad and wide, and relevant to health care and nursing.

Components of Complex Adaptive Systems

A CAS is composed of agents that interact within the system. These agents also may be considered a CAS embedded in a larger CAS. For example, an individual in a family is a CAS as well as an agent in the family. These agents act within the system according to patterned behavior. That behavior may self-organize at the CAS level, leading to new emergent behavior. The components of these networks are agents and patterns.

Agents

Agents are units or components of the system, which, as previously mentioned, can be individuals, birds in a flock, bees in a hive, or a component of a human system such as genes or neurons. These agents interact in a particular way, and their interactions and the patterns of interaction are the focus of CS, rather than understanding the agent in isolation. The interaction enables the system to function in a way that could not be understood from the examination of only the components.

Each agent also may be a CAS and, in turn, is also part of a larger CAS. For example, a nurse in a clinic is a CAS, as well as an agent in the CAS of the clinic. The nurse coevolves with the unit as the system emerges from the patterns of interactions. In this way, the nurse also contributes to and is affected by the organization of the unit.

Control of a CAS is highly dispersed and decentralized, and the overall behavior of the system is the result of multiple decisions by individual agents (Waldrop, 1992). The agents, as well as the system, are adaptive. Agents have fuzzy boundaries and simultaneously may be members of several systems. Examples include the immune system, a financial market, and a hospital unit.

Patterns

Patterns are formed by agents acting from a set of internalized rules. In a biochemical system, these patterns can be a series of chemical reactions; in an organization, they comprise the behavior of individuals or groups. Patterns and behaviors are the focus of understanding the CAS. Again, the emphasis is the relationships among the agents, rather than the agents themselves. Agents within a CAS have patterns of behavior that evolve. They absorb their past history and experiences, as well as respond to endogenous and exogenous changes. The CAS can develop rules that shape the interaction of the agents. Such systems are capable of emergent patterns that may be incorporated into the CAS's future behavior.

Characteristics of Complex Adaptive Systems

The following characteristics are part of the CAS. Many of these constructs are similar to some of the features of the mathematical and science disciplines (see **Table 6-3** for a summary of CAS characteristics). Here, however, they are applied in a more conceptual or theoretical framework, which allows them to be applied to clinical situations, thereby demonstrating both a patient and an organizational focus.

Connectivity

Agents or components of a system are connected to other components both within the system and within larger systems.

Complex Adaptive Systems Are Dynamic and Adaptive

A key characteristic of a CAS is that it is *dynamic*; that is, the system can adapt to changes in both its internal and external environments. The organism or organization demonstrates transformations of behavior through multiple modes of behavior. According to general systems theory, a system that loses its ability to maintain its equilibrium may cease to exist. Lindberg and colleagues (2008) note that nurses, physicians, and other healthcare

Table 6-3 Complex Adaptive Systems Concepts

Components
- Agents
- Patterns

Characteristics
- Connectivity
- CASs are dynamic and adaptive
- Simple rules allow CASs to function
- Emergence is a property of a CAS
- CASs are self-organizing
- Control is distributed rather than centralized
- Diversity maximizes self-organization
- CASs are deterministic
- CASs are exemplified by embeddedness (i.e., a CAS may be nested within a larger CAS)
- Coordination dynamics occur within a CAS
- CASs are sensitive to initial conditions
- Coevolution occurs with a CAS
- CASs are robust and adaptable

professionals often have an orientation toward homeostasis and strive to maintain the status quo both in physiology and in organizations. A healthy system often features processes that keep the system in a balanced or dynamic state of equilibrium so that the system can adapt to both internal and external stimuli. Complexity exists in the dynamic balance between stability and instability.

Goldberger (1996) provided a physiological illustration of this balance through a discussion of heart rate, rhythm, and cardiac output. At one extreme is a patient who is stable, but whose electrocardiographic tracing strip reflects heart failure with minimum variability. This lack of variability indicates a system that is unable to respond or adapt to changes or demands on the system. This is a most unhealthy, nonadaptive state. Conversely, fibrillation, in which the heart demonstrates chaotic, highly irregular, and unpatterned rhythms, is both dysfunctional and life threatening. These examples stand in contrast to a healthy cardiac system, which operates within the range of complexity so that there are continual alterations in the heart rate in response to small and large stimuli. Thus, the heart is capable of adapting to its changing environment by adjusting output.

Simple Rules Support Complex Adaptive Systems

It is posited in CS that a CAS operates by an adherence to a few *simple rules* that allow the system to function. These rules are not overly specific, written, or overt; rather, they are part of the function of the components of the system. A frequently cited example is used to illustrate some of the rules that allow a flock of birds to fly in a group. The following rules have been suggested by computer modeling: (1) Maintain a minimum specific distance from other birds; (2) match velocity with other birds in the flock; and (3) move toward the center of the mass of birds in the neighborhood. Imagine what it would take to give specific instructions to each bird, depending on the bird's location within the flock.

A different set of rules operate in a bee hive, where residents of the hive have different specific roles and each bee (the agent) adapts to certain external and internal environmental stimuli based on simple rules. When agents follow these rules, a form of collective behavior, a structure or a process that is more complex than the rules that produced it, emerges (Paley, 2007). These simple rules guide the CAS and allow it to act as a system. For example, an application of simple rules allows social insects such as bees to form a collective unit that enables them to behave like a single organism or system (Kauffman, 1995; Waldrop, 1992). Scientists and mathematicians have begun to discover some of these rules and are seeking to construct mathematical models to understand the behavior of the CAS—namely, its ability to behave as a single organism with multiple agents.

Emergence Is a Property of Complex Adaptive Systems

Emergence has been compared to novelty, flexibility, and the creative advancement of a system (Capra, 2002). Novel or new structures, patterns, properties, or processes can emerge during the process of self-organization in a CAS. Examples of emergence include the ways in which termites and ants build large complex structures that appear to have had an architect, designer, or structural engineer guiding the process. The human brain may operate in a similar fashion, as individual neurons (i.e., agents) operate locally and in networks through some simple patterns of reciprocal activation. In both cases, the collective structure or activity cannot be deduced from individual behaviors. These emergent behaviors can be innovative and creative. It is also a possibility that some emergent patterns will not be sustainable or adaptive over the long run.

Complex Adaptive Systems Are Self-Organizing

A cardinal property of a CAS is that it is *self-organizing*. Most CASs operate on a stability~instability dynamic. Self-organization requires appropriate conditions, often described as far from equilibrium or on the edge of chaos. This terminology indicates a zone that is closer to the instability pole where change can occur. Given its ability to exhibit emergent collective behavior, the CAS can self-organize into novel or new patterns. In this way, it moves away from a simple equilibrium or stable state and activates the nonlinearity inherent in the system. This evolution may lead to a new pattern and change the dynamics of the system. The important concept here is that these activities, behaviors, or patterns come from the CAS without the imposition of a central grand plan or control, or an externally imposed plan.

Control Is Distributed Rather Than Centralized

A characteristic of self-organization in a CAS is *distributed control*. This term implies that the agents or components do not act through a central agent or blueprint within or outside of the system. There is no central control that is responsible for the behavior or structures that emerge; rather, the CAS is a network of disparate agents exhibiting coherence and the ability to change without central direction or a single intelligent executive function. The commonality in the examples of emergence is that the activity or structure is produced by local interactions, without any central command center. This principle is often referred to as *distributed control* (Lindberg et al., 2008), previously addressed.

Unexpected complex results from the decentralized local interaction of agents often appear to mimic more centralized organized and planned activities that are evident in a growing number of disciplines (Paley, 2007). For example, the brain has approximately 100 billion individual neurons—agents interacting with one another through hormonal and other mediators, which are themselves often localized (Holt, 2004). The individual neurons have no cognitive capacity, but nonlinear interactions between them may generate higher-level cognitive functions. Distributed control is an important characteristic of self-organization. Nevertheless, the self-organization is not always independent of the environment, because often it is the environment to which the CAS adapts.

Complex Adaptive Systems Have Diversity

Diversity has been identified as a characteristic that maximizes self-organization. The greater the diversity of the components or patterns, the more robust and adaptable the system can be. Having diversity allows for the use of multiple resources to respond to external stimuli and internal adaptations (Lindberg et al., 2008). Diversity in a system provides for novelty and is a source of the capability for adaption. It is a key to innovation and long-term viability in both individuals and organizations. In addition, diversity has been demonstrated to be an essential ingredient in healthy ecosystems (Wilson, 1992). When the ecosystem is unhealthy and the environment is ruined, civilizations can collapse.

Complex Adaptive Systems Are Deterministic

CASs tend to have patterns that follow or are *determined by* earlier ones. This stands in contrast to stochastic or random systems, in which there is no predictability or coherent pattern from previous states. The CAS operates by applying simple rules, and often these patterns continue and are predictable in the short run. The tendency toward determinism can be cause for confusion because this characteristic coexists with emergence and self-organization. Even in complex emergence, there is generally a pattern that is not totally chaotic, but rather demonstrates a self-similar pattern.

Complex Adaptive Systems Are Exemplified by Embeddedness

Similar to the hierarchy of systems in systems theory, CASs exist in an ecological nest of *embeddedness*. Similar to systems theory, one can locate the level of the system as the focal system, with those systems within it being considered subsystems. This system is embedded then in larger systems, which form its context. It is important to locate the level that one is addressing to discuss it. Complexity scientists often refer to the concept of embeddedness as levels that represent (1) an external level as the context, (2) the middle level as the focus of the interactions among the agents, and (3) the inner level as the agents and behaviors within the focal system. All actions and dynamics influence and are influenced by all three levels, with each level influencing all of the others. The degree of cohesion between the three levels depends on each nested system's behaviors. When one of the nested systems experiences a change or perturbation, the entire system is affected. An example of how changes in a system can alter the network of embedded systems can be seen with fluctuations in the stock markets. In 2008, when the U.S. stock market experienced a crisis, stock markets around the world experienced the effects.

Coordination Dynamics Occur Within Complex Adaptive Systems

Coordination dynamics are context dependent and operate according to a three-part process of interaction between parts: (1) within a focal (or part of a) system, such as the firing of neurons within the brain; (2) between different parts of the same system, such as between the heart and the lungs; and (3) between other systems, the person, and the environment (Kelso & Engstrom, 2006). A significant amount of this interaction is related to self-organization. These coordinating elements interact with one another, as well as their surroundings, and they organize themselves into dynamic patterns.

Complex Adaptive Systems Are Sensitive to Initial Conditions

Given these dynamics, one can see how initial conditions could have a great impact on outcomes. Even a small perturbation in the system has the capacity to greatly alter the future structures, patterns, and processes. Lorenz (1993), a leading figure in chaos theory, noted that a small change in the initial condition of a system might trigger a chain of events that could lead to large-scale alterations of outcomes. The metaphor of the *butterfly effect* has become very popular. As small an input as a butterfly flapping its wings in Brazil can, at a critical point, alter the weather system so that a tornado occurs in Kansas. This highly sensitive nature of the CAS underscores the difficulty of making long-term predictions. Indeed, a condition in a certain time or space may significantly affect the dynamics of the system under certain conditions, but not others. Thus small inputs may have large effects, and large effects may have simple causes. For example, a person may be exposed to multiple viruses many times yet never become sick; in contrast, at a different time and place, just a minimum exposure may result in sickness.

Coevolution Occurs With Complex Adaptive Systems

When the environment includes other CASs, a process of reciprocal adaptive dynamics often occurs. In this case, two systems are simultaneously changing and self-organizing, a process termed *coevolution*. Many scientists cite coevolution and the adaptive changes that organisms and the universe have made as an explanation for evolution (Kauffman, 1995). An example might be the way in which a parasite and its host coevolve to form a single system, with each party benefiting from and adapting to the other, but evolving to a different system than either one independently (Lindberg et al., 2008).

Robustness and Adaptability

Robust systems are able to continue to function and adapt to changes within the system as well as changes in the environment. A robust system can respond to external and internal changes while still maintaining the integrity and function of the system. Some of this adaptability is related to the coordination of stability with disruption/transformation.

COMPLEX ADAPTIVE SYSTEMS, COMPLEX RESPONSIVE PROCESSES, AND ORGANIZATIONS

Several authors have applied CAS concepts to organizations (Plsek, 1997), while others have made a distinction between CASs and complex responsive processes (CRPs; Stacey, 2001) in applying complexity to systems. CAS is the term more widely used in the United States when dealing with HCOs. The following sections provide brief discussions of organizations from both perspectives.

Organizations as Complex Adaptive Systems

Plsek (as cited by the Institute of Medicine [IOM], 2001), in reference to organizational systems, defined a CAS as a system of individual agents who are interconnected, yet have freedom to act in novel and unpredictable ways. One agent's action changes the context for other agents, which illustrates how control is dispersed throughout the interaction among agents.

Applying complexity to organizational structure was advocated by Plsek (2001). He illustrated his advocacy for complexity first with an example of the mechanistic approach, and he then contrasted it with an example of complex, self-organizing behaviors. A good surgical team operates via a mechanistic approach, such that their actions are predictable and ordered. This is seen as the only viable approach, because an "either/or" perspective fears any approach that is not ordered. Thus the choice in the operating room is strict control—an ordered mechanistic approach that has both benefits and limitations. Plsek contrasts that example with a unit that is more complex and that self-organizes and emerges with creativity. In this area, new and novel behaviors occur. It is important to note that this emergent behavior can manifest as either innovation or error. Plsek advocated for an application of CAS concepts to describe a middle zone of complexity in which a CAS can act within a range of adaptability from highly ordered to an area of emergence, with the ability to adapt to different conditions.

Plsek (2001) criticized traditional management theory because of its emphasis on ways to establish order and control through the actions of a few people at the top of the organizational hierarchy. Jordan and colleagues (2009) described order and structure, as well as innovation, spontaneously coming about through self-organization. Emergent properties can be produced from self-organization of agents at lower levels, which then leads to patterns and order at higher levels, which in turn can reinforce existing patterns or create systems change. Plsek (1997) described the perspective of viewing the organization through the lens of a CAS, which would avoid the limitations associated with overcontrolled hierarchical organizations. By expressing general direction and a few basic principles, CAS leaders could allow enough flexibility for the adaptability and creativity of the organization to emerge.

It was contended that the organization could be able to achieve a balance by integrating a planned, ordered approach with a more flexible approach. Plsek used the metaphors of clockware (planned, rational, repeatable, standardized, and measured) and swarmware (exploring new possibilities, trials, freedom, autonomy, and intuition) to describe this process. By working at the edge of knowledge and experience or near the edge of chaos, maximum flexibility and innovation can be realized. Operating from this edge of chaos allows creativity to emerge, but at the same time, creates a need to balance the tension fostered by simultaneously maintaining the status quo and allowing creative change. In advocating for this blending of approaches, Plsek emphasized a need for interaction among agents to work through the tensions of perspectives as well as allowing new ideas to emerge.

Plsek (2001) described how a few simple rules can be demonstrated in organizations that allow for both functional order and creativity, citing the Internet as a prime example. He highlighted the many successful high-tech firms that have fewer rules, structures, and policies than their less successful competitors. Plsek identified three types of simple rules that can apply to organizations: (1) rules that point to a general direction such that management provides the general direction or goals for the organization; (2) prohibitions or regulatory and boundary-setting rules, which restrain and maintain standards and order; and (3) recourses, incentives, and permission-providing rules, which allow for innovation and rewards.

Lanham and colleagues (2009) also used the concept of CASs in an analysis of four studies dealing with primary care. These researchers found that the CAS was a useful and comprehensive theory to explore emergence of systems-level properties arising over time from local interactions among agents. They determined that practice-level quality is viewed best in holistic ways as systems issues rather than individual components. Thus, making an effort to improve the relationships among the members, rather than focusing on the individual components, allows for more effective strategies for improvement.

Organizations and Complex Responsive Processes

Organizational theorist Ralph Stacey (2001) applied complexity thinking to organizations and coined a new term, *complex responsive process* (CRP). Stacey objected to the systems approach, which he contended placed the organization and individuals at different explanatory levels. Instead, he focused on learning and knowledge creation. His premise is that organizational knowledge can be found in the relationships and conversations between people within an organization. The individual mind and the social world are the same process; thus knowledge is in perpetual construction. The potential for both continuity and change exist within these everyday conversations. Therefore, change comes from the interaction between or among individual people. The complexity concepts of self-organization, emergence, and nonlinear patterns of behavior are applied in this model as well.

Complex Responsive Processes and Relationship-Centered Care

CRP approaches have been promoted by Suchman (2006) as part of *relationship-centered care* (RCC) and through *complex responsive processes of relating* (CRPRs). RCC is based on a Pew–Fetzer task force effort to advance humanism in medicine in order to combat the objectivist and reductive approach of science-based practice. RCC went a step further by advocating the notion of patient-centered care and the biopsychosocial model. RCC is founded on four principles:

1. Relationships in health care include the personhood of the participant.
2. Affect and emotions are important components of these relationships.
3. Healthcare relationships occur in the context of reciprocal influence.
4. Genuine relationships in health care are morally valuable, and the patient–clinician relationship is central, but relationships of clinicians with one another, with the community, and within themselves are important as well (Beach, Inui, & The Relationship-Centered Care Research Network, 2006, p. 53).

Drawing on Stacey's work on CRP, Suchman (2006) used a process of CRPR to examine pieces of meaning and relating in each relationship encounter. These patterns reflect role structures, dominance hierarchies, and behavioral norms, as well as vocabulary, concepts, and knowledge (particular and specific). The self-organization of patterns in social process is ubiquitous. Self-organization at this level requires the simultaneous action of order~disorder and constraint~freedom. CRPR allows one to determine how these patterns are created and maintained. Suchman has applied this approach to patient–provider encounters, as well as to interprofessional relationships. These applications, which are often of a reciprocal nature, could have significant relevance to the relationships between nurses and patients.

IMPLICATIONS FOR PRACTICE

Practice as Complex Adaptive Systems

The IOM (2001) noted that complexity in the practice setting is a leading variable in the "significant unpredictability and variation in clinical outcomes." One can think of practice from the perspective of various sizes of systems. Microsystems, mesosystems, and macrosystems are all CASs that are related and connected through relationships (Roussel, 2014). It is through the connections within these systems that providers interact with patients, that providers interact with other providers, and so forth. The clinical microsystem, for example, is the frontline unit of care that interacts with the patient, and those interactions affect outcomes. High-performance clinical microsystems foster a positive culture of open and respectful interaction focused on the patient's and the provider's mutual goal of optimal patient outcomes (Batelden, Nelson, Edwards, Godfrey, & Mohr, 2003). Clinical microsystems are dynamic and sensitive to small changes such as the attitude of one of its members, which can have a major influence on group dynamics and patient outcomes.

Any number of CAS microsystem interactions can be cited as examples, but one of great current interest is the interaction that occurs during a transition in care. What happens when several clinical microsystems interact—as they do during transitions of care—in increasingly rapid cycles? Care transition is defined as hospital discharge of the patient or movement of the patient from one healthcare setting to another (Geary & Schumacher, 2012). Many of these transitions occur in the context of increasingly fragmented care. One of the strengths of using a CAS approach to clinical situations is that CAS concepts can be integrated with other models and theories to expand understanding. One useful model is Meleis's (2010) middle-range transition theory. As Geary and Schumacher (2012) point out, combining CAS concepts from CS with transition theory provides a powerful new lens through which to view care transitions and ultimately a means to improve transition outcomes within the current context of limited continuity and consistency in care.

Viewing Healthcare Organizations Through the Lens of Complexity

It is generally accepted that HCOs are examples of a high order of complexity systems because these organizations typically contain systems embedded within other systems. From a macrosystems perspective, each HCO is part of a larger entity. An individual healthcare facility could be part of a larger healthcare system that includes a number of other facilities. The individual facility or system is, in turn, part of the local and national healthcare system that provides for the comprehensive healthcare needs of the nation across care settings and services. From a microsystems perspective, the HCO is composed of a number of traditional administrative and service lines, all of which are divided into smaller units that provide a variety of focused services to specific populations.

In examining an organization such as an acute care facility, the number of different units within larger units is striking. For example, major units on the organizational chart may include nursing administration, nursing/patient care units, food services, pharmacy, rehabilitation services, diagnostics (laboratory and radiology), business management, and environmental services. Each of these major units, in turn, has subunits. For example, patient care units may be organized around body systems, such as cardiovascular surgery, orthopedics, or neurology. Nurses who work within these units become highly specialized in the care of the target population. These nurses tend to develop expert knowledge related to the care of this population and create a culture that addresses and supports the special problems and needs of the population of interest. Such a unit is also part of the system of nursing services, with the unit and nursing service interacting. Additionally, each unit interacts with other nursing units and departments such as rehabilitation, radiology, and food services.

The overall purpose of HCOs is to deliver high-quality, comprehensive care that is coordinated, integrated, and cost-effective. In *Crossing the Quality Chasm: A New Health System for the 21st Century* (IOM, 2001), six recommendations to improve the current healthcare system are outlined: Health care should be safe, effective, patient centered, timely, efficient, and equitable. In preparing its report, the IOM committee was guided by the belief that care must be delivered by systems that have been designed carefully and consciously. The committee noted the following:

> Such systems must be designed to serve the needs of patients, and to ensure that they are fully informed, retain control and participate in care delivery whenever possible, and receive care that is respectful of their values and preferences. Such systems must facilitate the application of scientific knowledge to practice, and provide clinicians with the tools and supports necessary to deliver evidence-based care consistently and safely. (IOM, 2001, pp. 7–8)

When describing systems in the report, reference is made to all systems that affect healthcare delivery, such as regulatory, insurance, and HCOs; here, the focus is limited to HCOs, though we fully recognize that other systems interact with and influence HCOs and healthcare delivery. All systems must have at least two core values that include to serve the needs of patients and to allow patients to retain control over and fully participate in their own health care. Viewing HCOs through the lens of CS provides a dynamic framework for examining HCOs as CASs.

Healthcare Organizations as Complex Adaptive Systems

CASs are special cases of complex systems. No format or guideline exists to help one determine precisely what qualifies as a simple system or a complex system, although individual and collective wisdom are thought to make the distinction. In complex systems, unpredictability and paradox are ever present, and some things will inevitably remain unknowable (Plsek & Greenhalgh, 2001). This section addresses some key issues related to the framing and understanding of HCOs in terms of contemporary and highly complex organizations. They include new models of HCOs, leadership, and research.

New Models of Healthcare Organizations

Models of organizational development and change based on linearity, vertical organization, hierarchal decision making, and controlled change strategies are outmoded and do not work within contemporary HCOs. New models are needed to understand the dynamic fast-paced volatility of healthcare delivery changes that influence HCOs.

New mental models must replace outdated ones, and CS offers a new paradigm. CS is as much a vehicle for change as it is for creating a lens to understand organizations and change (Norman, 2009). As defined by cognitive scientists, a *mental model* is a concept that refers to deeply held or ingrained assumptions or generalizations about external reality, which can take the form of patterns or images that, in turn, frame and focus how we understand the world (Werhane, 1999). Individuals construct mental models based on knowledge and experience gained in the past. These mental models are used then to understand the present, allowing the individual to make decisions and to act (Rouse & Morris, 1986). Two important points about mental models are noteworthy. First, mental models are socially learned and, therefore, incomplete. Second, because they are socially learned, they are open to change (Chen, Mills, & Werhane, 2008). Mental models shape the way we see the world, and they can change over time.

The past is populated with mental models that primarily represent only linear thinking. In fact, the complexity of modern-day HCOs and healthcare delivery makes simple linear thinking obsolete. To manage the escalating complexity in HCOs and healthcare delivery, healthcare professionals must abandon the unitary approach of linear models, accept unpredictability, respect and make use of autonomy and creativity, and respond flexibly to emerging patterns and opportunities (Plsek & Greenhalgh, 2001). This transformation requires incorporating a complexity perspective to better understand the dynamics of these organizations. As previously emphasized, a "both/and" perspective rather than an "either/or" assumption is appropriate.

New Models of Leadership

Leadership styles change in a culture of complexity. An understanding of the organization as a CAS allows its leaders to accommodate their leadership style by engaging the natural dynamics of groups to self-organize to new situations and changes in both the ecosystem and the internal system. One such model applied in a CAS milieu is sometimes referred to as an *emergent model of leadership*. In CAS networks, leaders are open, responsive catalysts; they are collaborative co-participants who are connected and adaptable and who acknowledge paradoxes. These leaders value people and are engaged, continuously emerging, and able to shift as processes unfold. They decrease the burden imposed by rules, help others, and are good listeners.

By contrast, in many traditional hierarchical linear-oriented systems, leaders value position and structure; they are controlling, in charge, autonomous, self-preserving, and disengaged; they hold and value formal positions, set rules, make decisions, and repeat the past. This system bears little resemblance to a CAS, in which there are a few simple rules and the self-organizing dynamics are understood, thereby allowing for emergent adaptive behavior.

Leaders who embrace complexity and the CAS perspective view their roles differently. With a vision that allows the system to evolve, they support and encourage emergence and self-organization, rather than being controlling and dictatorial. Creativity is stimulated and encouraged. Key stakeholders are supported as they work to find solutions to problems affecting them. The vertical authority gradient of the top-down hierarchy is flattened, and new collegial partnerships based on respect, trust, and values replace autocratic leadership.

To facilitate the creation of such leaders in this new age of CS, major changes must occur in how leadership is perceived and prepared through formal educational processes and mentorships. This effort will also require a receptive organizational environment with a new vision of an organizational culture.

New Models for Research

Viewing HCOs from a reductionist perspective and using the machine as a metaphor to understand dynamic and adaptive systems have clear limitations. The randomized controlled trial (RCT), often described as the gold standard of research design, comes from the tradition of reductionism and, therefore, is not sufficient for the nonlinear and dynamic nature of the CAS. This is not to say that RCTs and other research designs based on a reductionist foundation are not useful; rather, the key point is that envisioning these designs as the *only* approach to understanding is knowledge limiting. It is important for researchers to apply the appropriate model and methodology to investigations and be open to expanding paradigms and methods.

Researchers McDaniel, Lanham, and Anderson (2009) emphasize that because HCOs are CASs, the phenomena of interest tend to be dynamic and unfold in unpredictable ways, and these unfolding events are often unique. Current research designs and methodologies fail to capture either the dynamic nature of the area of interest or the unpredictable unique occurrences. McDaniel and colleagues (2009) note that the traditional classification of research as either qualitative or quantitative is distracting and often not helpful in this setting because both approaches begin with a question, build or test models, and aim to understand or explain the phenomena of interest. Neither category alone is a perfect match for CASs, although the use of mixed-methods models in conjunction with new methodologies will more likely capture the richness of CASs and lead to better understandings. Using qualitative~quantitative research embraces a "both/and" approach rather than an "either/or" philosophy.

One emerging approach is *action research*, in which researchers incorporate action perspectives to change organizational patterns by actively engaging stakeholders in the change process (Koch & Kralik, 2006). For example, researchers are also using other techniques such as *positive deviance* to discover a unit within an organization that has significantly better outcomes or better approaches to problems with similar resources and constraints and in which others hold the view that the unit or area is exceptional. A positive deviance approach can be used as a model for change in other areas of the organization. Another approach, *appreciative inquiry*, is used by researchers to discover and then amplify what works "well" within an organization and to discover the direction that the organizational team chooses to take based on what has transpired in the past. When this strategy is employed, a culture of positive innovation can flourish.

The state of the science of CAS research is developing as well. Bar-Yam (2000) developed techniques to study nonlinear dynamics in complex systems. McDaniel and Driebe (2001) applied CAS theory to the analysis of HCOs. Agar (2004) combined ethnographic approaches with agent-based modeling to understand social systems. Non-reductionist strategies also have been frequently applied to understand large-scale systems such as hurricanes (Sornette, 2006).

Maguire, McKelvey, Mirabeau, and Oztas (2006) conducted a survey of CS and organizational studies. The 2009 issues of the *Journal of Evaluation in Clinical Practice* include a collection of articles about CS, and an ongoing section appears in subsequent issues. The interest in HCOs and CASs is growing, and new research methodologies are emerging to support this interest.

Recently, complexity has been applied to clinical research. Understanding the human as a complex system has led to new approaches in clinical research. Systems biology, which examines the network structures and dynamics with regard to regulatory circuits, is exploring the system's robustness in regard to adaptation to external forces, internal stability, and graceful degradation, which allows for a gradual aging process (Kitano, 2002). Complexity has been applied to multiple organ dysfunction syndrome (Seely & Christou, 2000) and sepsis (Mann, Engebretson, & Batchinsky, 2013). Research techniques that track multiple points of physiological data using computers to analyze very large data sets are now available. One example of computational analysis of large data is analyses of fractal dynamics and presence of loss of complexity. Research in complexity is generally conducted with interdisciplinary teams, representing clinical, biological, mathematical, and computational expertise.

APPLICATION TO HEALTH CARE AND NURSING

Application to Clinical Care

With the advent of computers and the corresponding ability to manage large amounts of data quickly, interdisciplinary teams have begun to apply complexity concepts to physiology and the management of patient care. West (2008), a physicist, advocated a medical application of a complexity approach, using it to program life-support equipment to a more appropriate variability in healthy people. For example, he suggested that the patterns of respirations should be studied and that the finer variability be programmed into respirators, rather than relying on a mechanically regular pulsation. Use of the complexity concept in this way addresses the adaptive pattern that can be predicted in the short run. This kind of agent-based modeling simulates the operations of complex physiological behavior in an attempt to re-create and predict the appearance of complex phenomena.

A key notion in CS is that simple behavioral rules generate complex behavior. This principle facilitates developing supportive interventions to mimic that pattern. The pattern can be drawn from theory or from actual empirical data of an individual patient. In another application, a team of researchers in the Veterans Administration used detailed monitoring of heart rate variability in trauma victims to identify early changes in the autonomic nervous system, thereby allowing for earlier intervention than was possible with the existing technology (Salinas, 2010). This is also applied in some intensive care units where panels of biomarkers are fed into computers that can generate patterns that might indicate a loss of complexity, thus allowing for earlier detection of changes in the patient's condition. Other researchers have advocated for the use of complex systems modeling as a means to obtain a better understanding of the obesity epidemic (Hammond, 2009).

Application to Nursing

CS and its application to nursing, health care, and HCOs is emerging as a new paradigm capturing the interest of scholars across a number of diverse disciplines (see **Box 6-1**). The use of computers has assisted researchers in refining CS, which in turn, has inspired a new paradigm in scientific thinking. This paradigm shift has influenced the way people interpret the world.

SUMMARY

The concepts of complexity are pervading many areas of study and have multiple applications to health care. A paradigm based on CS is congruent with the holistic paradigm familiar to nursing. The ability to apply the science as well as the associated change in thinking about physiology, human beings, groups, and organizations has significant implications for the

Box 6-1 CS Application to Health Care

In this chapter, advanced practice nurses (APNs) are introduced to an important paradigm through which to view clinical practice and care environments in new ways. Clinically, nurses need to be aware of a new spectrum of thought that can capture the details and complexities of human physiology. Adoption of this paradigm will enable the APN to provide more individualized patient-centered care to augment the adaptive capacity of the human body. Because new research findings based on CS are becoming available, it is important for APNs to understand the terminology and conceptual framework so that they can apply this new knowledge to patient care. In addition, this paradigm shift will spawn numerous applications of emergent technologies in patient care.

The complexity paradigm has major implications for health care through its application to organizations and work environments. As organizations struggle to be more responsive to internal and external issues, the ability to be flexible, adaptive, and innovative becomes essential for survival. Many organizations are beginning to apply CS at all levels within the organization. Nurses at all levels must understand this important framework of CASs if they are to maximize their ability to function both individually and as part of teams to sustain a dynamic and relevant organization poised for innovation and change in response to the ever more complex healthcare environment.

discipline of nursing. In keeping with the holistic approach, it is important to remember that the complexity perspective is complementary to the reductionist model. Together, they offer a more complete and holistic view of the world. For further reading on CS and CASs, see **Table 6-4.**

Table 6-4 Sources for Further Reading

General References of Interest
Kauffman, S. (1995). *At home in the universe: The search for laws of self-organization*. New York, NY: Oxford University Press.
Kelso, J. A. S., & Engstrom, D. A. (2006). *The complementary nature.* Cambridge, MA: MIT Press.
Stacey, R. (2001). *Complex responsive processes in organizations*. New York, NY: Routledge.
Waldrop, M. M. (1992). *Complexity: The emerging science at the edge of order and chaos*. New York, NY: Simon & Schuster.
Zimmerman, B., Lindberg, C., & Plsek, P. (1998). *Edgeware: Lessons from complexity science for health care leaders*. Bordentown, NJ: Plexus Press.
Specific to Nursing
Lindberg, C., Nash, S., & Lindberg, C. (2008). *On the edge: Nursing in the age of complexity*. Bordentown, NJ: Plexus Press.
Website
Plexus Institute: http://www.plexusinstitute.org

DISCUSSION QUESTIONS

1. How does more diversity in the nursing profession relate to CASs?
2. How could some of the agent-based modeling concepts be applied to patient-centered care?
3. How could local units in a hospital or clinic setting apply concepts of self-organization to become more adaptive to situational demands?
4. How could the APN apply the concepts of a CAS to individual patient care?
5. Reflect on a professional or personal experience when a seemingly small incident had a much larger impact than expected. What did you learn from this experience?

REFERENCES

Agar, M. H. (2004). We have met the other and we're not all nonlinear: Ethnography as a nonlinear dynamic system. *Complexity, 10*(2), 16–24.

Anderson, R. A., Issel, L. M., & McDaniel, R. R. (2003). Nursing homes as complex adaptive systems: Relationship between management practice and resident outcomes. *Nursing Research, 52*(1), 12–21.

Baranger, M. (2009). *Chaos, complexity and entropy: A physics talk for non-physicists* (Unpublished manuscript). Massachusetts Institute of Technology, Boston, MA.

Bar-Yam, Y. (Ed.). (2000). *Unifying themes in complex systems: Proceedings of the International Conference on Complex Systems.* Cambridge, MA: Perseus Books.

Batelden, P. B., Nelson, E. C., Edwards, W. H., Godfrey, M., & Mohr, J. J. (2003). Microsystems in health care: Part 9. Developing small clinical units to attain peak performance. *Joint Commission Journal on Quality and Patient Safety, 11*, 575–585.

Beach, M. C., Inui, T., & The Relationship-Centered Care Research Network. (2006). Relationship centered care: A constructive reframing. *Journal of General Internal Medicine, 21,* S3–S8.

Capra, F. (2002). *The hidden connections.* New York, NY: Doubleday.

Chen, D. T., Mills, A. E., & Werhane, P. H. (2008). Tools for tomorrow's health care system: A systems-informed mental model, moral imagination, and physicians' professionalism. *Academic Medicine, 83*(8), 723–732.

Crabtree, B. F., Miller, W. L., & Strange, K. C. (2001). Understanding practice from the ground up. *Journal of Family Practice, 50*(10), 881–887.

Geary, C. R., & Schumacher, K. L. (2012). Care transitions: Integrating transition theory and complexity science concepts. *Advances in Nursing Science, 35*(3), 236–248.

Goldberger, A. (1996). Non-linear dynamics for clinicians: Chaos theory, fractals and complexity at the bedside. *Lancet, 347,* 1312–1314.

Hammond, R. A. (2009). Complex systems modeling for obesity research. *Preventing Chronic Disease: Public Health Research, Practice and Policy, 6*(3), 1–10.

Holt, T. (2004). *Complexity for clinicians*. Oxford, UK: Radcliffe Medical Press.

Institute of Medicine. (2001). *Crossing the quality chasm: A new health system for the 21st century.* Washington, DC: National Academy Press.

Jordan, M. E., Lanham, H. J., Crabtree, B. F., Nutting, P. A., Miller, W. L., Strange, K. C., & McDaniel, R. R. (2009). The role of conversation in health care interventions: Enabling sensemaking and learning. *Implementation Science, 4*(15). Open access BioMed Central. Retrieved from http://www.implementationscience.com/content/4/1/15

Kauffman, S. (1995). *At home in the universe: The search for laws of self-organization.* New York, NY: Oxford University Press.

Kelso, J. A. S., & Engstrom, D. A. (2006). *The complementary nature.* Cambridge, MA: MIT Press.

Kitano, H. (2002). Systems biology: A brief overview. *Science, 295*(560), 1162–1664.

Koch, T., & Kralik, D. (2006). *Participatory action research in health care.* Malden, MA: Blackwell.

Lanham, H. J., McDaniel, R. R., Crabtree, B. R., Miller, W. L., Strange, K. C., Tallia, A. F., & Nutting, P. A. (2009). How improving practice relationships among clinicians and nonclinicians can improve quality in primary care. *The Joint Commission Journal on Quality and Patient Safety, 35*(9), 457–466.

Liebovitz, L. S. (1998). *Fractals and chaos simplified for the life sciences.* New York, NY: Oxford University Press.

Lindberg, C., Nash, S., & Lindberg, C. (2008). *On the edge: Nursing in the age of complexity.* Bordentown, NJ: Plexus Press.

Lorenz, E. N. (1993). *The essence of chaos.* Seattle, WA: University of Washington Press.

Maguire, S., McKelvey, B., Mirabeau, L., & Oztas, N. (2006). Complexity science and organization studies. In S. R. Clegg, C. Hardy, T. B. Lawrence, & W. R. Nord (Eds.), *The Sage handbook of organization studies* (2nd ed., pp. 165–214). London, UK: Sage.

Mandelbrot, B. B. (1967). How long is the coast of Britain? *Science, 156,* 636–638.

Mandelbrot, B. B. (1982). *The fractal geometry of nature.* San Francisco, CA: W. H. Freeman.

Mann, E., Engebretson, J., & Batchinsky, A. (2013). A complex systems view of sepsis: Implications for nursing. *Dimensions of Critical Care Nursing, 32*(1), 12–17.

McDaniel, R. R., & Driebe, D. J. (2001). Complexity science and health care management. In J. D. Blaire, M. D. Fottler, & G. T. Savage (Eds.), *Advances in health care management* (Vol. 2, pp. 11–36). Stamford, CT: JAI Press.

McDaniel, R. R., Lanham, H. J., & Anderson, R. A. (2009). Implications of complex adaptive systems theory for the design of research on health care organizations. *Health Care Management Review, 14*(2), 191–199.

Meleis, A. (2010). *Transitions theory: Middle range and situation specific theories in nursing research and practice*. New York, NY: Springer.

Norman, C. D. (2009). Health promotion as a systems science and practice. *Journal of Evaluation in Clinical Practice, 15*(5), 868–872.

Paley, J. (2007). Complex adaptive systems and nursing. *Nursing Inquiry, 14*(30), 233–242.

Phelan, S. E. (2001). What is complexity science, really? *Emergence, 3*(1), 120–136.

Plsek, P. E. (1997). *Creativity, innovation, and quality.* New York, NY: McGraw-Hill.

Plsek, P. E. (2001). Redesigning health care with insights from the science of complex adaptive systems. In Institute of Medicine, Committee on Quality of Health Care in America (Ed.), *Crossing the quality chasm: A new health system for the 21st century* (pp. 322–335). Washington, DC: National Academy of Sciences.

Plsek, P. E., & Greenhalgh, T. (2001). The challenge of complexity in health care. *British Medical Journal, 323*, 625–628.

Richardson, K. A. (2005). Systems theory and complexity: Part 3. *Emergence: Complexity & Organization, 7*(2), 104–114.

Rouse, W. B., & Morris, N. M. (1986). On looking into the black box: Prospects and limits in the search for mental models. *Psychological Bulletin, 100*, 349–363.

Roussel, L. A. (2014). The nature of the evidence: Microsystems, macrosystems, and mesosystems. In H. R. Hall & L. A. Roussel (Eds.), *Evidence-based practice: An integrative approach to research, administration, and practice* (pp. 171–184). Burlington, MA: Jones & Bartlett Learning.

Salinas, J. (2010). *Analysis, classification, and complexity of physiologic signals to support medical decision support: Why is my computer smarter than me????* Presentation at University of Texas–Houston School of Nursing, February 2, 2010.

Seely, A. J. E., & Christou, N. V. (2000). Multiple organ dysfunction syndrome: Exploring the paradigm of complex nonlinear systems. *Critical Care Medicine, 28*(7), 2193–2200.

Sornette, D. (2006). *Critical phenomena in natural sciences: Chaos, fractals, self-organization and disorder: Concepts and tools* (2nd ed.). Berlin, Germany: Springer-Verlag.

Stacey, R. (2001). *Complex responsive processes in organizations.* New York, NY: Routledge.

Sturmberg, J. P., & Martin, C. M. (2009). Complexity and health: Yesterday's traditions, tomorrow's future. *Journal of Evaluation in Clinical Practice, 15*(5), 543–548.

Suchman, A. (2006). A new theoretical foundation for relationship-centered care: Complex responsive process of relating. *Journal of General Internal Medicine, 21*, 40–44.

Waldrop, M. M. (1992). *Complexity: The emerging science at the edge of order and chaos.* New York, NY: Simon & Schuster.

Werhane, P. H. (1999). *Moral imagination and management decision making* (pp. 11–12). New York, NY: Oxford University Press.

West, B. (2008). A physicist looks at physiology. In C. Lindberg, S. Nash, & C. Lindberg (Eds.), *On the edge: Nursing in the age of complexity* (pp. 97–123). Bordentown, NJ: Plexus Press.

Wilson, E. O. (1992). *The diversity of life*. Cambridge, MA: Belknap Press.

Wilson, T., Holt, T., & Greenhalgh, T. (2001). Complexity science: Complexity and clinical care. *British Medical Journal, 323*, 685–688.

Zimmerman, B., Lindberg, C., & Plsek, P. (1998). *Edgeware: Lessons from complexity science for health care leaders*. Bordentown, NJ: Plexus Press.