Resource Guide and Glossary for Nonlinear/Complex Systems Terms

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The development of the young science of complexity has been accompanied by an array of new concepts and terms. This section is designed to acquaint the reader with Complexity Science terms, many of which are used in the book. The description of each term in the Resource Guide and Glossary is accompanied by: first, a list of other relevant terms found in the glossary; and second, bibliographical references, with the complete list found at the end of the lexicon.

Adaptation:

In Darwin's Theory of Evolution, adaptation refers to the ongoing process by which an organism becomes "fit" to a changing environment. Adaptation occurs when modifications of an organism prove helpful to the survival of the species. These modifications result from both random mutations and recombinations of genetic material (for example, by sexual reproduction). Through the process of natural selection, the modifications that prove to aid in the survival of the organism may be selected for species survival as well. The idea of adaptation plays a very important role in the concept of a complex adaptive system, mostly associated with the Santa Fe Institute. Researchers at Santa Fe have suggested that natural selection operates on systems that already contain a great deal of emergent order. Adaptability is closely related to sustainability. Sustainable systems are ones that are capable of adaptation to a changing environment. The study of adaptation in various kinds of artificial life (see below) has demonstrated that adaptation may occur by some sort of change in the rules of interaction or the nature of interactions among the component agents. Thus, adaptation appears to consist in part of "learning" new rules through accumulating new experiences.

See: Complex, Adaptive Systems; Emergence; Genetic Algorithm

Bibliography: Asma (1996); Holland (1995); Kauffman (1995); Reid (2007).

Agent-based Models:

Computer simulations, derived largely from artificial life, which consist of semi-autonomous agents representing the factors being modeled and whose rules of interactions can be changed in order to see the emergent results. For example, the rules can be set up as either more cooperative or more competitive. The simulation is not expected to be a totally accurate representation of what is being modeled but, rather, to provide some insight into how changes in the rules can affect the outcomes observed. Agent-based models are becoming increasingly sophisticated, not only in terms of the possible range of agents' behaviors but also in terms of being embedded in richer environments that also play key roles in the ensuing simulation.

See: Artificial Life; Cellular Automata

Bibliography: Axelrod (1984); Axelrod & Cohen (2000); Epstein (2007).

Artificial Life:

The life-like patterns emerging in cellular automata and related electronic arrays. These emergent patterns seem organic in the manner in which they move, grow, change their shape, reproduce themselves, aggregate, and die. Artificial life was pioneered by the computer scientist Chris Langton, and experimented with extensively at the Santa Fe Institute. Artificial life has been instrumental in the creation of agent-based models that are used to study various complex systems such as ecosystems, the economy, societies, cultures, and the immune system. The study of artificial life is promising insights into natural processes leading to the emergence of structure and new properties.

See: Cellular Automata

Bibliography: Langton (1986); For a new perspective (technical) on artificial life see Griffeath and Moore, Eds. (2003).

Attractor:

A mathematical construct very important to the field of nonlinear dynamical systems. Nonlinear or complex systems can be marked by a series of “phases,” each of which displays the constraint of the behavior of the system in consonance with a reigning attractor(s). Such phases and their attractors can be likened (very loosely) to the stages of human development: infancy, childhood, adolescence, and so on. Each stage has its own characteristic set of behaviors, developmental tasks, cognitive patterns, emotional issues, and attitudes (although, of course, there is some variation among different people). Though a child may sometimes behave like an adult (and vice versa), the long term behavior is what falls under the sway of the attractor. Technically, in a dynamical system, an attractor is a pattern in phase or state space called a phase portrait that values of variables settle into after transient values die out as the system unfolds over time. More generally, an attractor can be considered a circumscribed or constrained range in a system that seemingly underlies and "attracts" how a system is functioning within particular environmental (internal and external) conditions. The dynamics of the system as well as current conditions determine the system’s attractors. When attractors change, the behavior in the system changes because it is operating under a different set of governing principles. The change of attractors is called bifurcation, of which there are various kinds. A bifurcation results when there is a change in parameter values toward critical thresholds. Sometimes the latter criticalization is known as a far-from-equilibrium condition (particularly in the Prigogine School).

See: Bifurcation, Far-from-equilibrium; Phase (State) Space

Bibliography: Abraham (1982); Goldstein (1994).

Examples of Types of Attractors:

Fixed Point Attractor: An attractor that is a particular point in phase space, sometimes called an equilibrium point. As a point it represents a very limited range of possible behaviors in the system. For example, in a pendulum, the fixed point attractor represents the pendulum when the bob is at rest. This state of rest attracts the system because of gravity and friction. In an organization a fixed point attractor would be a metaphor for describing when the organization is "stuck" in a narrow range of possible actions.

Periodic (Limit Cycle) Attractor: An attractor that consists of a periodic movement back and forth between two or more values. The periodic attractor represents more possibilities for system behavior than the fixed point attractor. An example of a period two attractor is the oscillating movement of a metronome. In an organization, a periodic attractor might be when the general activity level oscillates from one extreme to another. Or, an example from psychiatry might be bi-polar disorder where a person's mood shifts back and forth from elation to depression.

Strange Attractor: An attractor of a chaotic system is bound within a circumscribed region of phase space yet is aperiodic, meaning the exact behavior in the system never repeats. The structure of a strange attractor is fractal. A strange attractor can serve as a metaphor for creative activities in an organization in which innovation is possible yet there is a boundary to the activities determined by the core competencies of the organization as well as its resources and the environmental factors effecting the organization. A strange attractor portrays the characteristic of sensitive dependence on initial conditions (the butterfly effect) found in chaos.

See: Butterfly Effect; Chaos; Fractal; Sensitive Dependence on Initial Conditions.

Bibliography: Abraham (1982); Ott (2003); For the slight technical difference between a strange and chaotic attractor see Ott, Sauer, Yorke, 1994.

Basins of Attraction:

If one imagines a complex system as a sink, then the attractor can be considered the drain at the bottom, and the basin of attraction is the sink's basin. Technically, it is the set of all points in phase space that are attracted to an attractor. More generally, the initial conditions of a system evolve into the range of behavior allowed by the attractor. When a specific attractor(s) is operative in a system, the behavior of the system will be consonant with that attractor(s), meaning that a measurement of that behavior will be in the system's basin of attraction and thereby eventually converge to the attractor(s), no matter how unusual the conditions affecting the system.

Autopoeisis:

A systems-based theory developed by the Chilean scientists Humberto Maturana and Francisco Varela. Maturana and Varela define a living organism as consisting of a circular, autocatalytic-like process which has its own survival as its main goal in a manner reminiscent of Kant's definition of causality in living systems versus that found in machines. An autopoeitic system's self-referential structure endows it with closure in the sense of being autonomous with respect to outside influences. The idea of closure was developed to contrast with an overemphasis on openness in open systems theory. Autopoeisis is the main inspiration for the influential theory of social dynamics developed by Niklas Luhmann, which is more popular in Europe than in the USA. The management theorist Gareth Morgan points out that an organization's identity, strategies, and awareness of its market can be seen as an autopoeitic circularity. That is why organizations can get "stuck" in a rut of activity and become unadaptable to a changing environment.

See: Boundaries

Bibliography: Chandler & Van de Vijver (2000); Luhmann, Bednar, & Baecker (1996); Maturana and Varela (1992); Morgan (1997).

Benard System:

A simple physical system, consisting of a liquid in a container being heated from the bottom and which has been extensively studied by the Prigogine School because of it demonstration of self-organization and emergence. As the liquid in a container is heated from the bottom, at a critical temperature level (a far-from-equilibrium condition), there is the sudden emergence of striking hexagonally-shaped convection cells. Prigogine has termed these hexagonal cells "dissipative structures" since they maintain their structure while dissipating energy through the system and from the system to the environment. These "dissipative structures" are a good example of unpredictable emergent patterns since the direction of rotation of the convection cells is the result of the amplification of random currents in the liquid.

See: Dissipative Structures; Emergence; Far-from-equilibrium; Self-organization

Bibliography: Nicolis (1989); Nicolis and Prigogine (1989); Goldstein (1994).

Bifurcation:

The emergence of a new attractor(s) in a dynamical, complex system that occurs when some parameter reaches a critical level (a far-from-equilibrium condition). For example, in the logistic equation or map system, bifurcation and the emergence of new attractors takes place when the parameter representing birth and death rates in a population reaches a critical value. More generally, a bifurcation is when a system shows an abrupt change in typical behavior or functioning that lasts over time. For example, a change of an organizational policy or practice which results in a long-term change of the business' or institution's behavior can be considered a bifurcation.

See: Attractor; Dynamical System; Far-from-equilibrium

Bibliography: Abraham (1982); Guastello (1995).

Boundaries (Containers or “Closure”):

Processes of self-organization and emergence occur within bounded regions (e.g., the container holding the Benard System so that the liquid is intact as it undergoes far-from-equilibrium conditions). In cellular automata the container is the electronic network itself, which is "wrapped around" in that cells at the outskirts of the field are hooked back into the field. These boundaries or containers act to demarcate a system from its environment, and, thereby, maintain the identity of a system as it changes. Furthermore, boundaries channel the nonlinear processes at work during self-organization. In human systems, boundaries can refer to the actual physical plant, organizational policies, rules of interaction, and whatever serves to underlie an organization’s identity and distinguish an organization from its environment. Boundaries need to be both permeable in the sense that they allow exchange between a system and its environments as well as impermeable in so far as they circumscribe the identity of a system in contrast with its environments.

See: Autopoeisis

Bibliography: Chandler & Van de Vijver (2000); Eoyang & Olson (2001); Goldstein (1994); Luhman, Bednarz, & Baecker (1996).

Butterfly Effect:

A popular image coming out of chaos theory which portrays the concept of sensitive dependence on initial conditions (i.e., a small change having a huge impact like a butterfly flapping its wings in South America which eventually leads to a thunderstorm in North America). Some attribute the term "butterfly" in "butterfly effect" to the butterfly-like shape of the phase portrait of the strange attractor discovered by the meteorologist Edward Lorenz when he first discerned what was later termed "chaos." The butterfly effect introduces a great amount of unpredictability into a system because one can never have perfect accuracy in determining those present conditions which will be amplified and lead to an outcome drastically different from the outcome expected.

However, since chaotic attractors are not deterministic and not truly random and operate within a circumscribed region of phase or state space, there still exists a certain amount of predictability associated with chaotic systems. Thus, a particular state of the weather may be unpredictable more than a few days in advance; nevertheless, climate and season reduce the range of possible states of the weather, thereby adding some degree of predictability even into chaotic systems.

See: Chaos; Sensitive Dependence on Initial Conditions

Bibliography: Abraham (1982); Lorenz (1993); Ott (2003).

Catastrophe Theory:

A mathematical theory of discontinuous change in a system formulated by the French mathematician René Thom from his work in algebraic topology. A "catastrophe" is an abrupt change in a variable(s) during the evolution of a system that can be modeled by structural equations and topological folds. Catastrophes are governed by control parameters whose change of values leads either to smooth transition at low values or abrupt changes at higher, critical values. For example, the way a dog's mood can change abruptly from playful to aggressive can be modeled by a simple "catastrophe." In organizations, the presence of sudden change can similarly be modeled using catastrophe theory. In recent years, catastrophe theory has come to be understood as a part of nonlinear dynamical systems theory.

See: Bifurcation

Bibliography: Guastello (1995).

Cellular Automata:

One of the earliest species of artificial life, cellular automata are computer programs composed of a grid of "cells" (like a checkerboard), each cell of which turns on or off according to rules having to do with the on or off status of neighboring cells. For example, the rule might state that a cell be "on" if its four neighbor cells (east, west, north, and south) are also on. Emergent global patterns can then be observed that may move around the screen in a life-like manner (hence, “artificial life”). These emergent patterns can be quite complex although they emerge from very simple rules governing the connections among the cells. Early versions of cellular automata were conceived at the Institute for Advanced Study, Princeton, by eminent mathematicians as John von Neumann and Enrico Bomberi. The more familiar version was invented by the brilliant mathematician John Conway in his "Game of Life." Today, the study of cellular automata goes under the name artificial life (A-Life) because the exploration of cellular automata and their patterns at such places as the Santa Fe Institute has led to insights into the way structure is built-up in biological and other complex systems. Businesses and institutions can be modeled by cellular automata to the extent they are made up of interaction among people, equipment, and supplies. For example, the strength, number, and quality of connections among people or groups can be modeled by cells and rules among cells, so that how changes in the rules influence the emergence of patterns can be investigated. The hope is that cellular automata models will yield important insight into the dynamics of human systems.

See: Complexity; Emergence; Self-organization

Bibliography: Dyson (1998); Griffeath & Moore (2003); Langton (1986); Poundstone (1985).

Chaos:

A type of system behavior which although it displays random-like dynamics is actually deterministic, that is, underneath the apparent randomness is a hidden order or pattern. Chaos can be found in certain nonlinear dynamical systems when control parameters surpass certain critical levels. An often used example which has become something of an emblem for nonlinear dynamical systems is a nonlinear equation frequently used in populations studies. Changes in the key parameter value can result in a period-doubling route to chaos. The emergence of this kind of technically chaotic dynamic in a system suggests that simple rules can lead to complex results. Such systems are constituted by nonlinear, interactive, feedback relationships among the variables, components, or processes in the system. Chaotic time series of data from measurements of a system can be reconstructed or graphed in phase or state space as a chaotic or strange attractor with a fractal structure. Chaotic attractors are characterized by sensitive dependence on initial conditions so that although the behavior is constrained within a range, the future behavior of the system is largely unpredictable. However, unlike a random system which is also unpredictable, chaos is brought about by deterministic rules.

There is some measure of predictability due to the way the attractor of the system is constrained to a particular region of phase space. For example, if the weather is a chaotic system, particular states of the weather are unpredictable yet the range of those states is predictable. Thus, it is impossible to predict what the weather will be exactly on a particular date in August in New York, yet it is predictable that the temperature will fall within a range of 65-95 degrees Fahrenheit. That is, the climate acts as a constraint of the unpredictability of the state of the weather. In simulations of organizations, chaos has been seen to show up under certain circumstances, such as inventory or production processes, hospital admission rates, timing of procedures, and so on. Recent research has pointed to ways to control chaos by introducing particular perturbations into a system.

See: Attractor; Butterfly Effect; Control Parameter; Sensitive Dependence on Initial Conditions; Time Series

Bibliography: Lorenz (1993); Guastello (1995); Ott (2003); West (1990); West (2006).

Chunking:

A term coined by journalist Kevin Kelly (past editor of *Wired* magazine) to describe how nature constructs complex systems from the bottom up with building blocks (systems) that have proven themselves able to work on their own. This concept is widely appreciated by evolutionary biologists and has been highlighted by complexity pioneer John Holland as a key feature of complex adaptive systems. Holland used the image of children's building blocks, of different shapes and sizes, combined in a variety of ways to yield new creations like castles and palaces.

See: Emergence; Genetic Algorithm; Self-organization

Bibliography: Holland (1994); Kelly (1994).

Co-evolution:

The coordinated and interdependent evolution of two or more systems within a larger system, such as different species co-evolving within a wider ecosystem. There is feedback among the systems in terms of competition or cooperation and different use of the same limited resources. An example of co-evolution may be how alterations in a predator can alter the adaptive possibilities of the prey. Co-evolution and co-creation are also found in social systems(e.g., businesses or institutions can co-evolve in various ways with their suppliers, receivers, even competitors in terms of joint ventures and strategic alliances).

Co-evolution is also seen in the theory of symbiogenesis described below in which two early life forms existing in an apparently host-parasite relationship merged to become the one cell prototype of all "modern" cellular structures.

See: Feedback; Fitness Landscapes

Bibliography: De Duve, C. (2005); Kauffman (1995); Margulis & Sagan (2002); Reid (2007).

Coherence:

The cohesiveness, coordination, and correlation characterizing emergent structures in self-organizing systems. For example, laser light is coherent compared to the light emanating from a regular light bulb. That emergent structures show a kind of order not found on the lower level of components suggests that complex systems contain potentials of functioning that have not been recognized before. Businesses and institutions can facilitate and utilize the coherence of emergent structures in place of the imposed kind of order found in the traditional bureaucratic hierarchy.

See: Dissipative Structures; Emergence; Self-organization; Synchronization

Bibliography: Goldstein (1994); Haken (1981); Kauffman (1995); Nicolis & Prigogine (1989); Strogatz (2003).

Complexity:

A description of the complex phenomena demonstrated in systems characterized by nonlinear interactive components, emergent phenomena, continuous and discontinuous change, and unpredictable outcomes. Although there is at present no one accepted definition of complexity, the term can be applied across a range of different yet related system behaviors such as chaos, self-organized criticality, complex adaptive systems, neural nets, nonlinear dynamics, far-from-equilibrium conditions, and so on. Complexity characterizes complex systems as opposed to simple, linear, and equilibrium-based systems. There are many measures of complexity each differing according to the selected salient features of the system under investigation. Over the past two decades the sciences of complexity are increasingly being used to understand social system dynamics, including leadership, and human physiology.

See: Complex, Adaptive Systems; Nonlinear System; Self-organization; Swarmware and Clockware

Bibliography: Hazy, Goldstein, & Lichtenstein (2007); Holland (1994); Kauffman (1995); Kelly (1994); West (1990); West (2006)

Complex Adaptive System:

A complex, nonlinear, interactive system which has the ability to adapt to a changing environment. Such systems are characterized by the potential for the emergence of new structure with new properties. Complex adaptive systems (CASs) can evolve by random mutation, self-organization, the transformation of their internal models of the environment, and natural selection. Examples include living organisms, the nervous system, the immune system, the economy, corporations, societies, and so on. In a CAS, semi-autonomous agents interact according to certain rules, evolving to maximize some measure like fitness to their environment. The agents are diverse in both form and capability and they adapt by changing their rules and, hence, behavior, as they gain experience. Complex adaptive systems evolve historically, meaning they absorb their past history and experience, so that it affects their future trajectory. Their adaptability can either be increased or decreased by the rules shaping their interaction. Moreover, unanticipated, emergent structures can play a determining role in the evolution of such systems, which is why such systems show a great deal of unpredictability. A CAS has the potential for a great deal of creativity that was not programmed into them from the beginning. Considering an organization as a CAS shifts the way change is understood and approached. For example, change can be understood as the emergence of innovative structures resulting from enhanced interconnectivity as well as connectivity to the environment, the cultivation of diversity of viewpoint of organizational members, and the experimentation with alternative rules and structures.

See: Agent-based Models; Adaptation; Emergence; Genetic Algorithm; Self-organization

Bibliography: Holland (1994); Kauffman (1995)

Complex Responsive Processes

A way of understanding complex systems proposed by the organizational theorist Ralph Stacey to replace the technical and anti-humanistic bias he has argued underlies most studies of complex systems when applied to human dynamics. Building on the work of early social thinkers such as Norbert Elias and George Herbert Mead, as well as later psychodynamic theories, complex responsive processes have to do with how individual identity, behavior, and attitudes arise out of interactional dynamics in groups. Human interactions for Stacey are fundamentally comprised of symbolic communications, which encapsulate attitudinal dispositions of the body, behavior, emotions, and the mind. Rather than the complexity of human interaction being viewed through the lens of mechanical-style feedback, mathematical frameworks, or computational analogies, Stacey zeros in on the complexity of the communication webs linking people through their interactions. Out of interactions among persons arise social patterns that are sustained as well as changed by these interactions. From this perspective Stacey has reframed many complexity theory concepts as they relate to human behavior and interactions. One of the radical challenges he mounts involves questioning the existence of systems in human organizations of all types. In place of systems he contends are patterns of interactions that are maintained and changed through responsive processes among people in everyday relating.

See: Complex Adaptive Systems

Bibliography: Mead (2002); Stacey (2001); Stacey (2007).

Deterministic System:

A system in which the later states of the system follow from or are determined by the earlier ones. Such a system is described in contrast to stochastic or random systems in which future states are not determined from previous ones. An example of a stochastic system would be the sequence of heads or tails of an unbiased coin or radioactive decay. If a system is deterministic, this doesn’t necessarily entail that later states of the system are predictable from knowledge of the earlier ones. In this way, chaos is similar to a random system. For example, chaos has been termed "deterministic chaos" because, although it is determined by simple rules, its property of sensitive dependence on initial conditions makes a chaotic system largely unpredictable.

See: Chaos

Bibliography: Lorenz (1993)

Difference/Diversity

Research has demonstrated that complex systems thrive on heterogeneity of their components or agents in relation to one another. For example, Steve Page has shown how differences or diversity of perspectives, stemming from such factors as ethnicity, background experience, academic training, can lead to more creative outcomes of working groups. In a similar vein, research in nursing homes by Ruth Anderson and colleagues suggest that greater attention to interaction among *different* professionals—nursing assistants, RNs and nursing managers—and their different cognitive schema improve outcomes for patients.

Bibliography: Anderson, Issel, & McDaniel (2003); Page (2007)

> *Difference Questioning:* A group process technique developed by Jeffrey Goldstein that facilitates self-organization by generating far-from-equilibrium conditions in a work group. The process consists of several methods whereby information is amplified by highlighting the differences in perception, idea, opinion, and attitude among group members. Difference questioning does not aim at increasing or generating conflict, but, instead, tries to uncover the already differing standpoints. Moreover, the process takes place within boundaries that ensure the self-organization is channeled in constructive directions. Difference questioning aims at interrupting the tendency toward social conformity that robs groups of their creative idea generating and decision making potential. In other words, it strives to

allow a greater flow of information among the group members which has been shown to be correlated with a far-from-equilibrium condition, a condition in which the emergence of new order can take place.

See: Information; Self-organization

Bibliography: Goldstein (1994).

Dissipative Structure:

The term used by the Prigogine School (from Ilya Prigogine, winner of the Nobel Prize in chemistry) for emergent structures arising in self-organizing systems. Such structures are dissipative by serving to dissipate energy in the system. They happen at a critical threshold of far-from-equilibrium conditions. An example is the hexagonal convection cells that emerge in the Benard System when liquid in a container is heated. Other examples are the so-called "chemical clocks" demonstrated in the Belousov-Zhabotinsky reaction. These "chemical clocks" are composed of both temporal structures, such as a shift from one color to another, as well as spatial structures such as spiral waves. Hermann Haken, who founded the Haken School of Synergetics, uses the term “partly ordered”, to describe phenomena similar to Prigogine’s dissipative structure.

The phrase “dissipative structure” cleverly juxtaposes two terms usually kept apart in thermodynamics circles: “dissipative” and “structure”. “Dissipative” customarily refers to the loss of energy taking place during the transmutation of one kind of energy to another, for example, second law of thermodynamics and its central idea of entropy increase. Since an increase of entropy was eventually understood as a disintegrating tendency, “dissipative” then should carry connotations diametrically opposite to those of the building-up of “structure”, since the latter denotes some kind of endurance over time. Indeed, dissipative structures are often described as steady states, thus connoting something that is in a dynamic, rather than static equilibrium, or to use an analogy, like a vortex where its shape or organization remains intact although water molecules are in constant flux within it. By bringing these contrary terms together, Prigogine was calling attention to how in a dissipative structure heat transfer is not correlated with the dissolution of order but is actually the source of new order! Incidentally, one of Haken's terms for dissipative structures is "partly structured" again referring to the impermanent quality of these structures due to a constant flux of energy and matter passing through them.

See: Coherence; Emergence; Far-from-equilibrium; Synchronization

Bibliography: Haken (1981); Nicolis (1989); Nicolis & Prigogine (1989).

Dynamical System:

A complex, interactive system evolving over time through multiple modes of behaviors. Instead of conceiving entities or events as static occurrences, the perspective of a dynamical system is of a changing, evolving process following certain rules and exhibiting an increase of complexity. This evolution can show transformations of behavior as new attractors emerge. The changes in a system's organization and behavior are called bifurcations. Dynamical systems are deterministic systems, although they can be influenced by random events. Times series data of dynamical systems can be graphed as phase portraits in phase space in order to indicate the "qualitative" or topological properties of the system and its attractor(s). For example, various physiological systems can be conceptualized as dynamical systems, the heart for one. Seeing physiological systems as dynamical systems opens up the possibilities of studying various attractor regimes. Moreover, certain diseases can be understood now as "dynamical diseases" meaning that their temporal phasing can be a key to understanding pathological conditions.

See: Attractors; Bifurcation

Bibliography: Abraham (1982); Guastello (1995)

Emergence:

The arising of new, unexpected structures, patterns, or processes in a self-organizing system. These emergents can be understood as existing on a higher level than the lower level components from which the emergents emerged. Emergents seem to have a life of their own with their own rules, laws, and possibilities unlike the lower level components. The term was first used by the nineteenth century philosopher G.H. Lewes and came into greater currency in the scientific and philosophical movement known as emergent evolutionism in the 1920's and 1930's. In an important respect the work connected with the Santa Fe Institute and similar facilities represents a more powerful way of investigating emergent phenomena. In organizations, emergent phenomena are happening ubiquitously yet their significance can be downplayed by control mechanisms grounded in the officially sanctioned corporate hierarchy. One of the keys for leaders from complex systems theory is how to facilitate emergent structures and take advantage of the ones that occur spontaneously.

Recently, such phenomena as disease, health and remission are being discussed as emergent phenomena in the sense that they arise out of "lower" level substrate conditions but express properties different than those found on the "lower" level.

See: Self-organization

Bibliography: Cohen and Stewart (1994); Goldstein (1999); Goldstein (2006); Journal - Emergence: Complexity and Organization; Goldstein (2007); Richardson & Goldstein (2007).

Bibliography: Emergence in Biology - *Carroll (2005); De Duve (2005)*; *Margulis and Sagan (2002); Reid (2007); Sole & Goodwin (2000;* Emergence in Physics - *Anderson (1972); Laughlin (2006)*

Equilibrium:

Equilibrium is a term indicating a rest state of a system, for example, when a dynamical system is under the sway of a fixed or periodic attractor. The concept originated in Ancient Greece when the great mathematician Archimedes experimented with levers in balance, literally "equilibrium". The idea was elaborated upon through the Middle Ages, the Renaissance and the birth of modern mathematics and physics in the seventeenth and eighteenth centuries. "Equilibrium" has come to mean pretty much the same thing as stability, i.e., a system that is largely unaffected by internal or external changes since it easily returns to its original condition after being perturbed, e.g., a balanced lever on a fulcrum (i.e., a see-saw). More generally, equilibrium suggests a system that tends to remain at status quo. The notion of physiological homeostasis, which has had such a strong hold in medicine and nursing could be considered a type of equilibrium.

See: Attractor; Far-from-equilibrium

Bibliography: Goldstein (1994); Nicolis & Prigogine (1989). West (2006); Also, West's chapter in the current volume.

Far-from-equilibrium:

The term used by the Prigogine School for those conditions leading to self-organization and the emergence of dissipative structures. Far-from-equilibrium conditions move the system away from its equilibrium state, activating the nonlinearity inherent in the system. Far-from-equilibrium conditions are another way of talking about a criticalization in the values of parameters leading-up to a bifurcation and the emergence of new attractor(s) in a dynamical system.

See: Difference Questioning; Equilibrium; Self-organization

Bibliography: Goldstein (1994); Nicolis (1989).

Feedback:

The mutually reciprocal effect of one system or subsystem on another. Negative feedback is when two subsystems act to dampen the output of the other. For example, the relation of predators and prey can be described by a negative feedback loop because the growing number of predators leads to a decline in the prey population, but when prey decrease too much so does the population of predators because they will not have enough food. Positive feedback means that two subsystems are amplifying each other’s outputs, such as the screech heard in a public address system when the microphone is too close to the speaker. The microphone amplifies the sound from the speaker which in turn amplifies the signal from the microphone and around and around. Feedback is a way of talking about the nonlinear interaction among the elements or components in a system and can be modeled by nonlinear differential or difference equations as well as by the activity of cells in a cellular automata array. The idea of feedback forms the basis of system dynamics, a way of diagramming the flow of work in an organization founded by Jay Forrester and made popular by Peter Senge.

See: Interaction, Nonlinear

Bibliography: Eoyang & Olson (2001)

Fitness Landscape:

The idea of epigenetic landscapes was proposed in the 1930's by the population geneticist Sewall Wright and then reformulated by others including the British biologist and embryologist C. H. Waddington. Wright, building on R. A. Fisher’s notion that natural selection was the opposite of entropic dissipation, suggested a visual analogue to how selection worked genetically: genes were depicted in genotype “space” with organisms tied together into populations in an ecological “space.” In such a landscape, there was not just one adaptive “peak” which genes had to “climb” in their adaptive strategies but rather a variety of them. An epigenetic landscape therefore combined into one image the themes of selection, population structure, and adaptation.

To portray how embryos would have a variety of possible pathways for development, Waddington imagined a similar landscape in which development took place, a landscape replete with contours like “hills” and “valleys” to represent channels carved-out by selectional pressures (in Waddington’s terminology, “channeled” was referred to by “canalyzed”). The term “fitness landscape” was later adopted by Stuart Kauffman as a "graphical" way to measure and explore the adaptive (fitness) value of different configurations of some elements in a system. Each configuration and its neighbor configurations (i.e., slight modifications of it) are graphed as lower or higher peaks on a landscape-like surface (i.e., high fitness is portrayed as mountainous-like peaks, and low fitness is depicted as lower peaks or valleys). Such a display provides an indication of the degree to which various combinations add or detract from the system’s survivability or sustainability. An important implication from studying fitness landscapes is that there may be many local peaks or "okay" solutions instead of one, perfect, optimal solution. The use of fitness landscapes can be applied to gain insight into various organizational issues including which innovative organizational designs, processes, or strategies promise greater potential.

See: Adaptation

Bibliography: Weber & Depew (1994); Kauffman (1995).

Fractal:

A geometrical pattern, structure, or set of points that are self-similar (exhibiting an identical or similar pattern) on different scales. For example, Benoit Mandelbrot, the discoverer of fractal geometry, describes the coast of England as a fractal, because as it is observed from closer and closer points of view (i.e., changing the scale), it keeps showing a self-similar kind of irregularity. Another example is the structure of a tree with its self-similarity of branching patterns on different scales of observation, or the structure of the lungs in which self-similar branching provides a greater area for oxygen to be absorbed into the blood. Strange attractors in chaos theory have a fractal structure. The imagery of fractals has been popularized by the fascinating graphical representations of fractals in the form of Mandelbrot and Julia Sets. Unlike the whole numbers characteristic of our usual dimensions (e.g., two or three dimensional drawings), the dimension of a fractal is not a whole number but a fractional part of a whole number such as a dimensionality of 2.4678.

Many measures of healthy physiologic complexity appear to show a fractal or fractal-like pattern in the sense of a similar or affine structure at different scales of resolution, for example: heart rate, breathing rate, blood counts. Degradation of the complexity of such patterns are also now thought to be associated with aging and many diseases and conditions, like Parkinson's disease, atrial fibrillation, congestive heart failure and cancer.

See also: Chaos

Bibliography: Field & Golubitsky (1996); Goldberger (1996); Mandelbrot (1977); Mandelbrot (1982); Schroeder (1991); West (1990); West (2006).

Genetic Algorithm:

A type of evolving computer program developed by the computer scientist John Holland whose strategy of arriving at solutions is based on principles taken from genetics. Basically, the genetic algorithm uses the mixing of genetic information in sexual reproduction, random mutations, and natural selection at arriving at solutions. In an analogous manner to the way a genetic algorithm learns better solutions through the mixing of patterns and an openness to random or chance events, a complex, adaptive system can adapt to a changing environment through a mixing of previous internal models of their environment. Thus, genetic algorithms can provide insight into the creative process of problem solving or decision making.

See: Complex, Adaptive System; Randomness

Bibliography: Eoyang & Olson (2001); Holland (1994).

Graph Theory (Social Networks)*:*

The mathematical theory that studies the properties of networks or webs of connections. A graph consists of edges (linkages) connecting nodes (what's connected). Examples of networks studied by graph theory include the internet, the economy, and genetic landscapes. Although graph theory is a purely mathematical discipline, the term is being included here because it is providing a theoretical foundation for the very influential and growing field of social network theory. The latter is providing rich insights into the dynamics of complex systems in general. For example, social network theory using graph theory has been discovering the complex structures of the internet, communities, employees connected within and outside their work organizations and so forth.

See: Scale-free Network; Small World Network

Bibliography: Kilduff & Tsai (2003); Newman, Barabasi, Watts (2006); Trudeau (1993); Watts (1999).

Information:

Originally, information in the technical senses referred to the bits of a message, as opposed to "noise," in a communication channel (formulated in Information Theory by the mathematician Claude Shannon building on earlier work done by Harry Nyquist and Ralph Hartley). Information has come to mean the bits of data that are the elements that are processed by the computer as information processor. "Noise" has a disorganizing effect in its way of disrupting redundant patterns so that novelty can come about in the emergent structures resulting from self-organizing processes. In terms of organizations, information is the cognate in social systems of what energy is in a physical system. According to Gregory Bateson, information is "a difference that makes a difference." In terms of social systems this refers to the differences among group members' perspectives on what is going on in the system. Information is not mere data: it is data that is meaningful to organizational members. An organization that is low in the flow of information is one in equilibrium or tending to maintain its status quo; whereas, an organization that is high in informational flow is in a far-from-equilibrium state in which dramatic changes can take place. Recent years have seen the birth of a new field entitled quantum information science which is playing an important role in the development of quantum computers and so-called quantum teleportation, both relying on the strange nature of quantum entanglement. These new fields reveal that information is increasingly seen as a basic constituent of the world around us or as the renowned physicist John Wheeler once put it, "It comes from bit!"

See: Redundancy

Bibliography: Goldstein (1994); Darling (2005).

Initial Conditions:

The state of a system corresponding to the beginning of a period of observing or measuring it. The initial conditions are what is assessed at any particular time, and to which one can compare any later observation, measurement, or assessment of the system as it evolves over time. For example, chaotic systems demonstrate sensitive dependence on initial conditions, meaning that the nonlinearity strongly amplifies slight differences in initial conditions, thereby rendering impossible the predictability of later states of the system.

See: Chaos; Sensitive Dependence on Initial Conditions

Bibliography: Lorenz (1993); Ott (2003).

Instability:

The condition of a system when it is more easily disturbed by internal or external forces or events, in contrast to a stable system that will return to its previous condition when disturbed. A pencil resting vertically on its eraser or a coin resting on its edge are examples of systems that have the property of instability because they easily fall over at the slightest breeze or movement of the surface they are resting on. An unstable system is one whose attractors can change, thus, instability is a characteristic of a system near or at bifurcation (or far-from-equilibrium).

See: Bifurcation; Equilibrium: Far-from-equilibrium

Bibliography: Nicolis (1989)

Interaction:

The mutual effect of components or subsystems or systems on each other. This interaction can be thought of as feedback between the components as there is a reciprocal influence. In contrast, the effect of a pool cue on a cue ball is not interactive since the cue balls movement does not immediately affect the pool cue itself. For example, in cellular automata, it is the programmed rules that shape the kind of interaction occurring among neighboring cells. Complex adaptive systems are nonlinear, interactive systems.

See: Feedback; Nonlinear

Bibliography: Eoyang and Olson (2001).

Linear System:

Technically, any system in which the change of values of its variables can be represented as a series of points suggesting a straight line on a coordinate plane, hence, the term "*line*ar" for line. More generally, a linear system is one in which small changes result in small effects, and large changes in large effects. In a linear system, the components are isolated and noninteractive. Real linear systems are rare in nature since living organisms and their components are not isolated and are made-up of rich interactions.

See: Nonlinear System

Bibliography: Abraham (1982)

Minimum Specifications:

The management theorist Gareth Morgan's term for processes encouraging self-organization by avoiding an overly top-down, imposed design on an organization or work group. These processes can include such elements as mission statements, guiding principles, boundaries, creative challenges, and so on. The key is for leadership to provide the minimum specifications so a work group itself has creative space to accomplish its work. Minimum specifications are analogous to the simple rules governing cell interactions in studies of cellular automata.

See: Cellular Automata; N/K Model

Bibliography: Morgan (1997); Zimmerman, Lindberg, Plsek (2001).

Neural Networks:

Electronic automatons, similar in some ways to cellular automata, that offer a simplified model of a brain. As such, neural networks are devices of machine learning that are based on associative theories of human cognition. Using various algorithms and weightings of different connections between "neurons," they are set up to learn how to recognize a pattern such as learning a voice, recognizing a visual pattern, learning some form of robotic control, manipulating symbols, or making decisions, and so on. Generally, neural nets are composed of three layers: input neurons; output neurons; and a layer in-between where information from input to output is processed. Initially the network is loaded with a random program, then the output is measured against a desired output which prompts an adjustment in the "weights" assigned to the connectivities in response to the "error" between the actual and desired output, and this is repeated many times. In this way, the neural network learns. In a sense, a neural net has to be able to discover its own rules. Changing the rules of interaction between the "neurons" in the network can lead to interesting emergent behavior. Hence, neural nets are another tool for investigating self-organization and emergence.

See: Adaptation

Bibliography: Allman (1989).

Nonlinear System (Nonlinearity):

Technically, any system where the data points representing values of its variables can be represented as a curvilinear pattern on a coordinate plane, hence, “*non*linear” for not-a-line. That is, the system’s dynamics are more appropriately represented by nonlinear and not linear functions. More generally, a system in which small changes can result in large effects, and large changes in small effects. Thus, sensitive dependence on initial conditions (the butterfly effect) in chaotic systems illustrates the extreme nonlinearity of these systems. In a nonlinear system the components are interactive, interdependent, and exhibit feedback effects. Complex adaptive systems are nonlinear systems.

Before the advent of chaos and complexity theories during the past thirty-five years, nonlinear functions were mostly relegated to appendices in textbook because of their refractoriness to analytic solutions. But now, because of both advances in computational approaches to nonlinear functions and the recognition of the crucial role played by interactions in most systems of interest, it is increasingly recognized that examples of nonlinear systems are presumably endless. Thus, human physiology is replete with nonlinear systems, such as the cardiac, circulatory, and immune systems. In addition, in social systems nonlinearity seems to be the norm since they are constituted by mutually reciprocal interactions among the members of social groupings and such interactions are appropriately modeled by nonlinear rather than linear equations.

See: Linear; Sensitive Dependence on Initial Conditions

Bibliography: Eoyang and Olson (2001); Goldstein (1994); Guastello (1995); Scott (2005); West (1990); West (2006).

Novelty:

One of the defining characteristics of emergent patterns is their novelty or innovative character. Indeed, that is why such phenomena are termed "emergent" since they introduce new qualities into the system that were not pre-existing in it. An example is the novel nature of the "dissipative structures" that arise in nonlinear systems at far-from-equilibrium conditions. This novelty is neither expected, predictable, nor deducible from the pre-existing components. Moreover, this novelty is not reducible to the lower level components without loosing its essential characteristics. An issue, therefore, for practitioners working with complex systems, is to determine which system processes are necessary for the emergence of novelty. That is, novel outcomes demand novel processes that prompt a system to produce novel structures and practices. In organizations, novel emergent outcomes are typically termed innovations. The study of the diffusion of innovations was pioneered by the late Everett Rogers (see below).

See: Bifurcation; Emergence; Far-from-equilibrium; Self-organization

Bibliography: Goldstein (2006); Rogers (2003); Van de Ven & Garud (1994).

Parameters:

Variables in the mathematical equations used to model system behavior. Changes in the values of these variables can affect the system's behavior.

Control Parameters: These parameters often model some kind of external influence on a system that facilitate a far-from-equilibrium condition or, in other words, expedite a bifurcation. An example is temperature in the Benard System, which at a critical value prompts self-organization and the emergence of hexagonal convection cells when a particular liquid in a container is heated from the bottom.

Order Parameters: Parameters that represent some global emergent characteristic of a system as opposed to variables of lower level components. The shift to order parameters signifies recognition that emergent phenomena need to be investigated on their own terms.

Lambda Parameter: A parameter used by the computer scientist Chris Langton to get at the range where self-organization is most likely in cellular automata. As such the lambda parameter is a control parameter.

See: Bifurcation; Cellular Automata

Bibliography: Haken (1981); Langton (1986).

Phase (State) Space:

An abstract mathematical space which is used to display time series data of the measurements of a system. The dimensions of phase or state space correspond to the number of variables used to characterize the state of the system. For example, the phase space of a pendulum would consist of two dimensions: the speed of the bob; and the distance of the bob from the vertical resting state. Phase space is very helpful for observing the patterns that result as systems evolve over time. Please note that time is usually not one of the explicit dimensions of the phase space, a role that time does play in a straight graphical depiction of a time series.

> *Phase Portrait:* The geometrical patterns shown in phase space as a system evolves. These portraits may be attractors such as fixed point, periodic, and strange attractors. They can also include repellors (the opposite of attractors) and such interesting patterns as saddles (in which there are attractor(s) in one direction and repellor(s) in another direction) and separatrices, or boundaries between two basins of attraction.

See: Attractors; Chaos

Bibliography: Abraham, et. al. (1991); Guastello (1995)

Positive Deviance:

Experiments or deviations from the norm in a social system that can lead to positive change. The phrase itself “positive deviance” is a kind of oxymoron, since it pairs the constructive term “positive” with the negative term “deviance,” the latter term carrying quite a bit of pejorative associations precisely because it pertains to deviations from the norm. For example, members of a society practicing “fringe behavior” are often called deviants. However, branding “deviance” with such derogatory outcomes sets up a bias that protects the norm with a halo of righteousness while condemning deviations-from-the-norm as degenerate. If this bias were strictly enforced, we would never have gained most of the great scientific and social advances of human history. All such major innovations and transformations, in one way or another, relied on radical departures from the norm. Both the Copernican and the American Revolutions are cases in point.

A social interventional method termed "Positive Deviance" developed by Jerry and Monique Sternin identifies novel experiments in complex social systems—deviations from the norm—and harnesses them to generate positive outcomes. "Radical" ideas from organizational outliers are reframed as solutions with the potential of bringing about significant social system change. According to Jerry Sternin, in many communities facing seemingly intractable problems, there are certain individuals or groups (positive deviants) with the same access to resources as other community members whose special practices, strategies or behaviors generate better results.

Bibliography: Sternin & Choo (2000); Sternin (2003).

Power Laws:

A type of mathematical pattern in which the frequency of an occurrence of a given size is inversely proportionate to some power (or exponent) of its size. For example, in the case of avalanches or earth quakes, large ones are fairly rare, smaller ones are much more frequent, and between these extremes are cascades of different sizes and frequencies which take place a moderate number of times. Power laws define the distribution of catastrophic events in self-organized critical systems. Systems with power law distributions are marked by invariance with respect to scale and universality, the latter term referring to remarkably similar dynamics across quite different systems. Power laws are associated with fractal-like patterns since the pattern is self-similar with respect to scale. In this regard power law signatures have been discovered in heart inter-beat variability and are suspected in many other physiological phenomena.

See: Fractal; Scale-free Network; Self-organized Criticality; Sensitive Dependence on Initial Conditions

Bibliography: Bak (1996);Barabási (2002); Schroeder (1991); West (2006).

Redundancy:

The existence of repetitive patterns or structures. In an important sense, redundancy refers to order in a complex system in the sense that order is defined as the existence of structures that maintain themselves over time (i.e., they are stable). In information theory, redundancy refers to repetition in patterns of messages in a communication channel. If the message contains these redundancies, they can be compressed further. For example, if a message contains a series of two hundred and fifty 1s, then the message could be compressed into a command which effectively says "and then repeat 1 250 times" instead of writing out all two hundred fifty 1s. Self-organizing processes demand some element of redundancy which can be considered as a "fuel" for the processes leading to emergence. In other words, novel patterns come from a recombination of redundant patterns.

See: Information; Novelty

Bibliography: Campbell (1982); Poundstone (1985).

Scale:

The level at which a system is observed. For example, one can observe the coast of England from a satellite or from a jet liner or from a low flying plane, or from walking along the coast, or from peering down into the sand and rocks on a cove beach that you are standing on. Each of these perspectives is of a different scale of the actual coast of England. Fractals are geometric patterns that are self-similar on different scales.

See: Fractal; Power Law

Bibliography: Kaye (1989); Schroeder (1991)

Scale-free Network

A type of network, studied by means of graph theory, in which some of the nodes act as highly connected hubs but most other nodes have a lower degree of connectivity. They are called “scale-free” because their structure and dynamics are independent of the system's size defined in terms of number of nodes. A scale-free network has the same features no matter what number of nodes is in the network. Scale-free networks also exhibit a power law distribution and may be more resilient in the face of loss of connectednes than hub networks which cannot withstand the loss of the hub.

See: Fractal; Scale; Graph Theory; Small Worlds

Bibliography : *Barabási (2002); Watts (1999).*

Self-organization:

A process in a complex system whereby new emergent structures, patterns, and properties arise without being externally imposed on the system. Not controlled by a centralized, hierarchical "command and control" center, self-organization is usually distributed throughout a system. Self-organization requires a complex, nonlinear system under appropriate conditions, variously described as "far-from-equilibrium" or criticalization. Studied in physical systems by Ilya Prigogine and his followers, as well as the Synergetics School founded by Hermann Haken, self-organization is now studied primarily through computer simulations such as cellular automata, Boolean networks, and other phenomena of artificial life. Self-organization is recognized as a crucial way for understanding emergent, collective behavior in a large variety of systems including: the economy; the brain and nervous system; the immune system; ecosystems; and the modern large corporation or institution. The emergence of new system order via self-organization is thought to be a primary tendency of complex systems in contrast to the past emphasis on the degrading of order in association with the principle of entropy (second law of thermodynamics). In recent perspectives, rather than fighting against entropy, self-organization can be understood as a way that the total entropy of a complex system along with its environment(s) increases.

Now that we have a better handle scientifically on how self-organization takes place, it is easier to recognize instances of it in the world around us. For example, self-organization could be an appropriate way of understanding how a hospital staff may spontaneously re-organize itself to respond more effectively to a sudden influx of critically ill patients. This is what seems to have happened, for example, at Beekman Downtown Hospital in Manhattan during the tragedy of 9-11-2001 when the staff coalesced into novel treatment teams to handle the tremendous inflow of seriously wounded victims. Self-organization may also take place in innumerable other ways, for example, the change in family dynamics that results when a family member enters a hospice program, or the emergence of novel ways to provide care to a seriously ill that comes from interactions among the patient, nurses, physicians, other healthcare professionals, support staff and family members when patients have multiple chronic diseases.

See: Coherence; Dissipative Structures; Emergence; Far-from-equilibrium

Bibliography: Eoyang & Olson (2001); Goldstein (1994); Nicolis (1989); Nicolis & Prigogine (1989).

Self-organized Criticality:

Formulated by the late physicist Per Bak, a phenomenon 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. Such 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 these systems follow power laws, and because fractals also show a similar mathematical pattern, it may be 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.

See: Bifurcation; Catastrophe; Instability; Power Law; Self-organization

Bibliography: Bak (1996).

Sensitive Dependence on Initial Conditions:

The property of chaotic systems in which a small change in initial conditions can have a hugely disproportionate effect on outcome. Sensitive dependence on initial conditions is popularly captured by the image of the butterfly effect. Sensitive dependence on initial conditions makes the behavior of chaotic systems largely unpredictable because measurements at initial conditions always will contain some amount of error. The late mathematical metereologist Edward Lorenz uncovered this concept in his work on weather forecasting. He noticed that a seemingly insignificant difference in an initial parameter in a forecasting system modeled on his computer led to very different forecasts.

See: Chaos; The Butterfly Effect

Bibliography: Lorenz (1993); Ott (2003).

Small World Network:

A type of graph network in which the connectivity among nodes leads to the formation of pathways linking an unusually large number of nodes. The small world phenomenon was made famous in the play(movie) “Six Degrees of Separation” and the “Kevin Bacon number”, which refers to the idea that any actor can be linked through his or her film roles to the actor Kevin Bacon. In both of these, it has been shown mathematically and through experimentation that nearly everyone on the planet is remarkably linked by no more than six linkages in a network comprising all the relationships between people**.**

See: Graph Theory; Scale-free Network

*Bibliography***:** *Barabási, A. L. (2002); Watts (1999).*

Stability:

The opposite of "instability," the property of a system which stays pretty much the same after being disturbed by internal or external forces or events. For example, the deeper the keel of a sailboat, the more stable it is regarding the wind and currents. A running gyroscope is stable with respect to changes affecting its centrifugally determined level plane. Stability is sometimes used as a synonym for equilibrium or with the state of a system circumscribed within a particular attractor regime.

See: Equilibrium; Far-from-Equilibrium; Instability

Bibliography: Nicolis (1989); Nicolis & Prigogine (1989); Ott (2003).

Swarmware and Clockware:

Two terms coined by the editor of *Wired Magazine* Kevin Kelly for two antithetical management processes. "Clockware" are rational, standardized, controlled, measured processes; whereas "swarmware" are processes including experimentation, trial and error, and risk-taking. Clockware processes are seen in linear systems whereas swarmware is what happens in complex systems undergoing self-organization as a result of the nonlinear interaction among components.

See: Cellular Automata; Complex Adaptive System; Self-organization

Bibliography: Kelly (1994).

Symbiogenesis:

A theory about the emergence of new biological forms put forward by Lynn Margulis which posits that cooperation or symbiosis among two or more distinct types of organisms can lead to the emergence of radically novel types of organisms. It is believed that primitive organisms called eukaryotes incorporated certain elements of the aerobic bacteria that had been ingested into them and that out of this symbiotic relation, the more advanced prokaryotic cells resulted with the novel features of nuclei and membranes. Symbiogenesis manifests a new interpretation of evolution whereby other mechanisms besides variation and selection may be at work. It also represents a growing recognition of the importance of cooperative relationships among species instead of the more typical emphasis on competition and predator-prey relationships.

See: Co-evolution; Emergence

Bibliography: De Duve (2005); Margulis & Sagan (2002); Reid (2007)

Synchronization:

A phenomenon that can occur in complex systems in which system components or agents align themselves in a startling coherence. A striking example can be seen in the dramatic synchronization of lighting in certain species of fireflies (what we used to call "lightning bugs" as children). This can be seen inside the Great Smoky National Park near Elmont, Tennessee, during mid-June at about 10 PM every night when thousands of fire flies flash together according to a highly synchronized pattern: After six seconds of total darkness, thousands of lights flash in perfect synchrony six times in three short seconds; the pattern then repeats itself over and over again. A similarly synchronization of firing among fireflies can be observed in parts of Thailand. Research has shown that synchronization takes place without any "leader" firefly. Instead synchronization develops out of the interaction among the fireflies. Specifically, under the right conditions, signals from one to the other become resonated in concert. In human systems, synchronization is evident during sporting events when fans in a stadium combine movement into the famous "wave" of hands.

A destructive kind of synchronization was responsible for the collapse of the Tacoma Narrows Bridge on December 11, 1940. A confluence of high winds and too much structural coherence that was built into the bridge led to a resonance of vibrations affecting the bridge leading to the collapse of the bridge's structure.

See: Coherence

Bibliography: Strogatz (2003)

Time Series:

A collection of measurements of the variable(s) of a system as it evolves over time. Traditionally, times series data were graphed with time on the x-axis and some system variable on the y-axis. For example, the time series of an oscillating (periodic) system such as a forced pendulum or a metronome would show a curve depicting the speed of the pendulum bob going up and down like hills and valleys over time. However, as the result of dynamical systems theory, time series are now usually graphed in phase or state space with either two or more variables marking each dimension, or one variable is mapped against a time lagged version of the same variable. By graphing times series data in phase space, attractors can be identified more easily. Our ability to graph such times series and to determine their attractors has been greatly accelerated by the rise of the personal computer.

See: Attractor; Phase Space

Bibliography: Guastello (1995); Ott, Sauer, Yorke 1994)

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