SELF-ORGANIZATION, EMERGENCE, AND ADAPTATION
IN OTHER WORDS... COMPLEXITY

While it might be sensible to begin an essay on self-organizing, adaptive, complex systems exhibiting emergent behavior by defining those terms, this is a surprisingly difficult task. After reading several books and many articles either devoted to or referencing the topic, I was left with a string of questions I was unable to answer including simple ones such as "what makes a system complex?" Even an explicit search for a simple definition of complexity uncovered something of a mess. One early researcher in complex systems theory was cited as saying that "he once gave a presentation which set out 32 definitions of complexity."[1] The curated online source Scholarpedia has this to offer:

> *Quantitative or analytic definitions of complexity often disagree about the precise formulation, or indeed even the formal framework within which complexity is to be defined. Yet, there is an informal notion of complexity based upon some of the ingredients that are shared by most if not all complex systems and processes.*[2]

In the big scheme of things, the science of studying complex systems is quite new, emerging within the last 20 years, and so it's not surprising that the concepts are new as well. The human mind has nothing to compare these to and so definitions are not very illuminating until one already understands the concept being defined. This round-about approach to tackling a new concept for which one has no frame of reference seems to be the only mechanism we have at our disposal. We need to establish a pattern, a meta-feature to recognize and name, a process which might require many iterations for more abstract concepts. In this essay, I hope to guide the reader through enough iterations around this circular path to eventually spiral into a shared understanding of complexity, and following that, to inquire into the ways in which complex system theory might inform our understanding of higher cognitive functions. To begin, we can at least settle on the fact that we are examining "systems" or *sets of interacting or interdependent entities, real or abstract, forming an integrated whole*[3].

Our first loop takes us through the field of physics in which the process of self-organizing systems can be most simply introduced. Molecules of water move about randomly in liquid form but when cooled to the freezing point, they *self-organize* into crystalline structures. We have all

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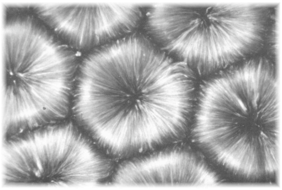
[1] Wikipedia Complexity. (n.d.) Retrieved March 12, 2009, from Wikipedia: http://en.wikipedia.org/wiki/Complexity

[2] Olaf Sporns (2007) Complexity. 2(10):1623, revision #39900. Retrieved on March 10, 2009 from Scholarpedia: http://www.scholarpedia.org/article/Complexity

[3] Wikipedia System (n.d.) Retrieved March 14, 2009, from Wikipedia: http://en.wikipedia.org/wiki/System.

viewed this process enough times to leave us fairly confident that this is a predicable result of water reaching the freezing point, and yet the shape of the resulting crystal formation is difficult if not impossible to predict[4]. If liquid is moved away from a state of equilibrium by the application of heat, the liquid will self-organize into hexagonal convection cells.



In the above image, aluminum filings have been added to a heated fluid, photographs of which were captured over a period of 10 seconds illustrating the rise of the fluid at the center of the cell, the spreading out to the edges of each hexagonal cell, and then flow back down below the surface of the fluid.[5] The patterns in snowflakes and convection cells *emerge* spontaneously as a result of the process of self-organization. *Emergent* properties are those which could not have been predicted through a reductive analysis of the component molecular parts. They appear out of the whole and are more than the sum of the parts. Clouds and hurricanes are self-organizing as are lasers and stars, but these all fall into the realm of the inanimate. To find self-organizing, *adaptive* systems, ones that will exhibit not only emergent properties but also *emergent behavior*, we must move into the realm of the living. Examples of living systems considered *complex* include:

ant colonies (and communities of other social insects),
neuronal connections,
cities,
economies,
evolution,
immune systems,
homeostasis in biological organisms, and
flocking birds & schooling fish.

An often-used example of a self-organizing, adaptive, complex system is the ant colony. Each ant plods along acting only in response to what it encounters: other ants, pheromone trails, food, obstacles, and barometric pressure, among other things. Despite the limited repertoire of a single ant, their colonies not only self-organize, they exhibit global intelligent behavior, *emergent behavior*, that could not have been predicted even if the actions of individual ants were well understood. The intelligence of the colony emerges from the actions of single ants in the absence of a grand plan to achieve it. In other words, the intelligence emerges from the *bottom-up*, ant by ant, instead of from the *top-down;* the emergent behavior is not the result of the execution of a

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[4] Hermann Haken (2008) Self-organization. 3(8):1401, revision #45083. Retrieved March 11, 2009 from Scholarpedia: http://www.scholarpedia.org/article/Self-organization.

[5] Author unknown. (n.d.) Rayleigh-Benard Convection Cells. Retrieved on March 12, 2009, from NOAA Environmental Technology Laboratory Website: http://www.etl.noaa.gov/about/eo/science/convection/RBCells.html

coordinated plan. A few of the more interesting *emergent* behaviors of ant colonies include the maximal spacing of food store, trash heap, and cemetery; the building of higher colony entrance berms in preparation for monsoon season; and the re-allocation of worker resources when needed.

If the actions of independent ants appears so convincingly to be coordinated, how are scientists so sure they are not? Through careful observation of individual ants, the rules of being an ant have been fed into countless computer simulations and low & behold, the same emergent features of the real ant colony arise in the simulations. These ant simulators show that if you have enough agents following the rules of *antness*, the intelligence of the colony will emerge quite reliably. There is no foreman, no coordinator, no sovereign, despite the confusingly named queen whose only role is to mate on a single day and lay eggs for the remainder of the life of the colony which can last 15 to 20 years.[6] It's worth noting the number of ants matters a great deal, something that turns out to be true in general of complex systems. Too few ants and nothing will emerge, but cross a threshold in ant population and some of the features such as food store and trash heap will emerge, cross another threshold and even more ant colony properties emerge such as the ant cemetery.

The colony establishes foraging patterns by virtue of the fact that each ant senses and follows the strongest pheromone trail, leaving its own trail as it goes, thereby strengthening the trail. In this act, an individual ant is both influenced by and influences its fellow ants creating a *positive feedback loop* in the process. The strongest pheromone trail is followed, thereby making it even stronger. Despite acting entirely on local information, a global system forms. As it turns out, positive feedback loops are essential to self-organization, but if left unchecked, they result in systems that quickly play themselves out, such as hurricanes and cancer.[7]

That longevity of the ant colony is the result of *adaptation* which allows the colony to invent solutions to novel problems presented by the environment. A flood, a spray of insecticide on the trail, or an exhausted food source all represent challenges to the life of a colony and the solutions to these and other challenges are arrived at through the actions of rogue ants. It turns out that the ants that find new paths around flood zones & insecticide or the ones that discover a new food source are those that wander off the pheromone trail. These rogue ants represent a creative element in the system referred to as *quenched disorder*. Without this inherent randomness in the system there would be no adaptation. Clearly, there is a delicate balance between the rule-following ants and the rogue ants. If all the ants are rule-followers the colony will be too rigid and the resulting stasis will lead to the extinction of the colony at the first major challenge. If there are too many rogue ants the colony will never self-organize in the first place. In addition to quenched disorder, *negative feedback loops* support adaptation of the colony. For instance, if there are too many ants on foraging duty, the system must have a mechanism for feeding this information back in to create a change. Some ants will need to stop foraging and change to a different job, but who tells them to do this? As is the case with all the systemic adjustments, the

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[6] Gordon, D.M. (2003) The organization of work in social insect colonies. Complexity 8: 43-46. pg 4

[7] Theise, N. From the Bottom Up. Tricycle Magazine. Summer 2006. pp 24-27

change in colony worker allocation does not come about as the result of some global monitoring function, but instead emerges from of the ability of an ant to detect the roles of other ants it meets on the trail. Harvester ant researcher Deborah Gordon describes the process here:

> *When ants meet, they touch with their antennae. Antennae are the organs of chemical perception. When an ant uses its antennae to touch the antennae or body of another, it can perceive the colony-specific odor that all nestmates share. We found that in addition to the colony odor, P. barbatus ants have an odor specific to their task, because the temperature and humidity conditions in which an ant works alter its cuticular hydrocarbon profile (Wagner et al 1998, 2000, 2001). For example, a forager makes long trips outside the nest in hot, dry air, and this increases the proportion of n-alkanes in its hydrocarbons. An ant may assess the task of an ant it meets using these task-specific odors, so that an ant can evaluate its rate of encounter with ants of a certain task.*
>
> *[...]*
>
> *In laboratory studies, we found that an ant's decision whether to perform midden (trash collection) work depends on its recent rate of brief antennal contact with midden workers (Gordon & Mehdiabadi 1999).* [8]

An ant's role as forager or midden worker is evident in its scent due to variations of the colony scent caused by the environmental conditions specific to its role. In the case of the harvester ants studied by Deborah Gordon, what appears to be relevant in task allocation for the colony are the *patterns* detected by each individual ant. Observing a single ant touching antennae with the ants that it meets could be interpreted as one ant telling another ant what to do. Instead, it's believed that the frequencies and ratios of these ant-to-ant communications are building up patterns that allow an individual ant to adjust to what its encounters are telling it about the current task allocation.[9] To summarize, the organization of the colony as a whole, and the adaptation that changing conditions require of it, percolate up from a single ant responding to its own sensory perceptions in the absence of any global control. The colony organizes and is maintained through positive feedback loops (existing pheromone trails are reinforced) and negative feedback loops (too many foragers causes some ants to switch to different roles) as well as a crucial element of randomness.

Economist Brian Arthur was taught that negative feedback loops are a central and dominant force in the maintaining of equilibrium in economic systems,[10] but his observations led him to believe that positive feedback loops were equally influential, a position that proved so radical in academic circles that it almost derailed his career. In the field of economics, positive feedback loops translate to increasing returns, something Arthur's professors claimed were rare and short-lived. i.e. not relevant to the maintenance of economic systems which, oddly, are still

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[8] Gordon, D.M. (2003) The organization of work in social insect colonies. Complexity 8: 43-46

[9] Gordon, D.M. (2003) The organization of work in social insect colonies. Complexity 8: 43-46. pp. 3

[10] Waldrop, M.M. (1992) Complexity, The emerging science at the edge of order and chaos (pp. 35). New York: Simon & Schuster

predominantly thought of as systems in equilibrium. Though it may generally be true that economies are dominated by negative feedback loops, Arthur could see that *positive* feedback loops had a pivotal role to play during economic transition events such as the adoption of new technologies. The dynamic of a positive feedback loop in the early stages of competing technologies could be described as *them that has, gets*. These loops are especially interesting when they run counter to the prevailing wisdom that a free economy will always reward, and so sustain, "the best and most efficient technologies."[11] Arthur met with such resistance to the idea that positive feedback loops could derail a market's *natural selection* of the best technology that he started collecting examples of cases where clearly superior technologies perished in favor of inferior ones. Among his examples of successful inferior technologies are the VHS home video recorder, the QWERTY keyboard (intentionally designed to slow typists down to prevent typewriter jams), and the gasoline engine. Through accidents of history or an early lead in market share, relatively small tilts in the market led to historically large results, an aspect common to most complex systems.

The human version of an ant colony is a city, and while there are some notable cases in which cities were planned (Washington D.C, for instance) the predominant mechanism for their development is spontaneous self-organization. Cities, though organic, chaotic, and unplanned, develop clear patterns. There are homes clustered based on socioeconomic factors, businesses grouped based on product, and neighborhoods of bars that cater to a particular clientele. In his book *Emergence* (2001), Steven Johnson cites the silk merchants of Florence's Ponte Vechio and San Francisco's gay neighborhood, The Castro, as two such patterns, the former having persisted for over 900 years.[12] There are no town meetings to decide where the "gay" neighborhood will be, there are no executive decisions directing segregation along class lines (though it can often appears as though there are) and yet these kinds of patterns develop time and time again. It is only through the examination of patterns, already played out in history, that we are able to see the predictability of emergence. While we can predict that neighborhoods with unique personalities will form, it's impossible to predict where a neighborhood will emerge and what its particular nature will be. In the case of the self-organization of cities, as in economies, though there are conditions under which emergence is predictable, the nature of what emerges is almost impossible to predict. Though human societies are guaranteed to develop currency, religion, and art, the actual material for the currency, the mythology & practices of the religion, and the aesthetics of the art will be unique and ever-changing.

The development of a brain has parallels to that of the ant colony as well. A given neuron fires as a result of what its neighbors are doing. The strength of any given neuronal connection (synapse) is analogous to the strength of an ant colony's pheromone trail. The relationship between ants and pheromonal trails is not only analogous but also nested as illustrated in the following passage from a scientific article on the foraging behavior:

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[11] Waldrop, M.M. (1992) Complexity, The emerging science at the edge of order and chaos (pp. 35). New York. Simon & Schuster

[12] Johnson, S. (2001) Emergence. The connected Lives of Ants, Brains, Cities, and Software. (pp 102). New York: Scribner

> *Interactions between ants and the environment are integrated neurally. Each individual's behaviour is based on local information (pheromone trail) processed through a flux of signals- neurons, action potentials, neurotransmitters (Millonas, 1992). On average, any neuron forms thousands of synapses with other neurons. At some synapses, dendrites of the neuron receive incoming information from other neurons; at other synapses, axons from the neuron provide information to other neurons. In higher animals there are billions of neurons with trillions of synapses, and as a result the response of any one neuron may appear trivial, and the complexity of the central nervous system (CNS) may seem overwhelming, but not when the CNS is viewed as a self-organizing system in which simple rules (a neuron can either fire or not) operating from neurons, local circuits, subcortical nuclei, and cortical regions, to systems and systems of systems lead to complex organization (Damasio, 1994).* [13]

While the development of brains is fascinating in and of itself, it's even more interesting to realize that living organisms are elaborately nested trees of self-organizing systems. Embryonic development and the immune systems are both examples of self-organizing, complex, adaptive systems exhibiting emergent properties. The human organism is a vast network of cells, a small percentage of which carry our DNA, the remainder being bacterial and essential to our development and ongoing survival. Each cell responds only to the chemical messages it receives, the state of its immediate cellular neighbors (whether human or bacterial), and its internal state. From the large numbers of these interacting sub-units, an elaborate system of systems emerges.

By now we've iterated through enough examples to streamline the rather cumbersome expression that describes these systems: *self-organizing, complex, adaptive systems exhibiting emergent properties*. As it turns out, when one refers to the study of *complexity*, the rest of those terms are implicit. Complex systems, i.e. those with "numerous components capable of structured interactions that generate emergent phenomena"[14] are both self-organizing and adaptive.

Patterns of the meta-processes of self-organization, emergence, and adaptation are apparent in systems transcending the domains of physics, biology, chemistry, sociology, economics, and computer science. The patterns revealed are ones in which the presence of large numbers of autonomous agents, acting on local information, spontaneously self-organize into larger structures exhibiting emergent properties. These larger structures can, in turn, be autonomous agents acting on local information and so new systems of systems can self-organize forming a hierarchy of emergence. In his book *Complexity*, Waldrop tells the story of the scientists, one of whom was Brian Arthur, who grappled with the creation of a new science devoted to the study of these patterns across disciplines. These scientist eventually formed the Santa Fe Institute. One of

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[13] Provenza, F.D., Villalba, J.J., Cheney, C.D. and Werner, S.J. (1998) Self-organization of foraging behaviour : From simplicity to complexity without goals. (pp. 205) Nutrition Research Reviews 11, 199-222.

[14] Olaf Sporns (2007) Complexity. 2(10):1623, revision #39900. Retrieved on March 10, 2009 from Scholarpedia: http://www.scholarpedia.org/article/Complexity

these scientists, John Holland, describes the many levels of organization in complex adaptive systems:

> *...a complex adaptive system has many levels of organization, with agents at any one level serving as the building blocks for agents at a higher level. A group of proteins, lipids, and nucleic acids will form a cell, a group of cells will form a tissue, a collection of tissues will form an organ, an association of organs will form a whole organism, and a group of organisms will form an ecosystem.*[15]

Though the science of complex systems theory now exists, it still not clear what the forces and limitations are governing complex systems. The process of self-organization is ubiquitous in nature and it appears to override the second law of thermodynamics: *the entropy (disorder) of an isolated system increases over time, approaching a maximum value at equilibrium*. The key word here is *isolated*. In nature, systems are rarely isolated and as has been seen, there are circumstances in which order wins over disorder. When does something emerge and when doesn't it? When does a system make a big-leap in adaptation? There appears, as in the case of ant colonies, to be a critical population density required to trigger the emergence of certain features. The same can be said of the emergence of cities in the Middle Ages. There was an urban explosion shortly after 1000 C.E.[16] This rapid coalescing is similar to the formation of snowflakes at the freezing point and the explosion of wild-flowers in spring. These are examples of the *phase transitions*--changes in state that occur as a result of changing conditions or energy flowing into or out of a system. The transformation of water from liquid to solid at the freezing point is an example a first-order phase transition.[17] First order phase transitions are those that occur rapidly after crossing a critical threshold. If you lower the temperature of water below 32 degrees Fahrenheit, the water will freeze. During this phase transition, water molecules move from the chaotic organization of the liquid state to the ordered organization of the solid state. Raise the temperature above 32 degrees and the water molecules move from order back to chaos. In the case of complex systems it's as if the system is hovering at the critical "freezing point", oscillating back and forth continuously. There is a dynamic and delicate balance maintained between order and chaos. Tip too far to one side and you have stasis. Tip too far in the other direction and you have chaos which will lead to an extinction event. It might not seem intuitive to think of these as transition states at all since they are continuous, but they are distinguished from the rapid first order phase transitions by referring to them as *second order* phase transitions. It is this type of ongoing transitional state in which all complex systems exist. In all living systems, stasis = death.

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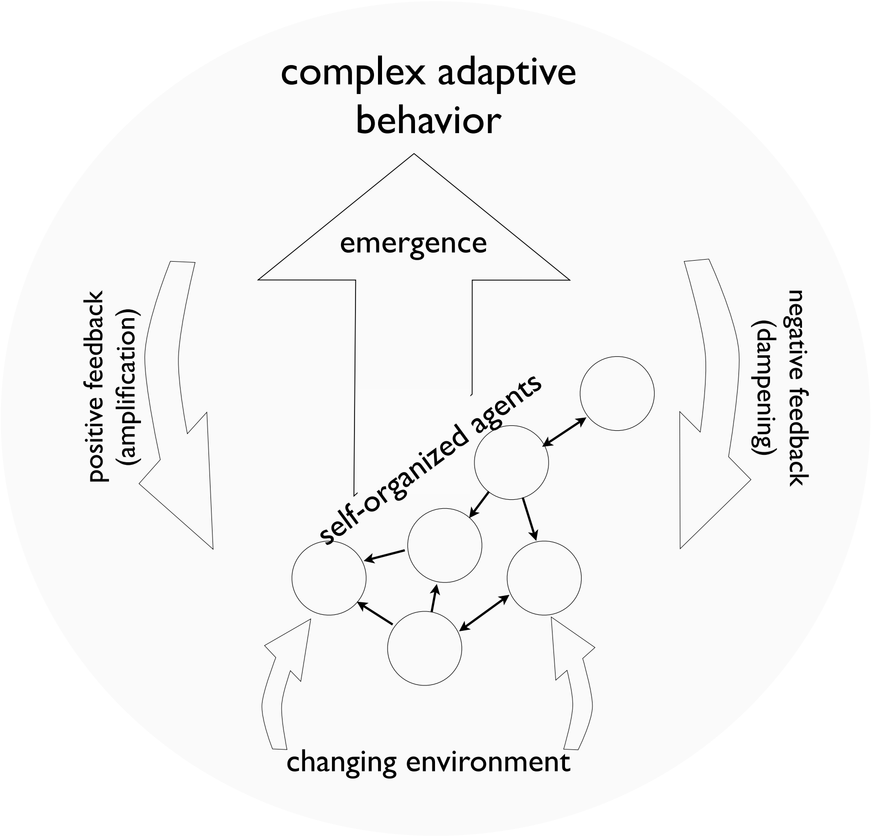
[15] Waldrop, M.M. (1992) Complexity, The emerging science at the edge of order and chaos (pp. 145). New York: Simon & Schuster

[16] Johnson, S. (2001) Emergence. The connected Lives of Ants, Brains, Cities, and Software. (pp 109-110). New York: Scribner

[17] Waldrop, M.M. (1992) Complexity, The emerging science at the edge of order and chaos (pp. 229). New York. Simon & Schuster

One of the Santa Fe Institute scientists, artificial life researcher Chris Langton, coined the term "edge of chaos" to describe this dynamic state where adaptation is ongoing, periodically pushed into periods of "growth" or rapid adaptation. Langton borrows a term from evolutionary biology to describe these periodic rapid changes: *punctuated equilibrium*. It is during these rapid changes that extinction events are most common, for instance a hurricane making landfall. In most cases, abrupt environmental changes create circumstances that cannot be adapted to and result in extinction events, but in some cases the massive changes occur as a result of forces from *within* the system. For instance, a bubble can be created in the stock market as the result of a positive feedback loop, but that loop and the subsequent crash are the results of the compounded acts of individuals.

The mathematics used to analysis self-organization and punctuated equilibrium events is rigorous, to say the least, but the concepts are well worth understanding even if the mathematics is elusive. When viewed conceptually, the processes and dynamics of complex systems constitutes a shift in worldview away from reductionist and dualistic views and can inform one's thinking across numerous domains. These concepts are summarized in the following diagram[18]:



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[18] Adapted from diagram on Complexity. Retrieved on March 9, 2009 from Wikipedia: http://en.wikipedia.org/wiki/File:Complex-adaptive-system.jpg

In Emergence, Steven Johnson lists five principles of complex systems, summarized as follows:

Numbers matter
There are critical numbers of agents needed for emergent properties to arise. A system may have several critical thresholds, past which new properties and/or behaviors will emerge.

Ignorance is useful
Having individual agents capable of assessing the overall state of the system is not only unnecessary, it can introduce undesirable behavior.

Random encounters are key
Complex systems rely on random encounters which allow for adaptive behavior.

Look for patterns
Pattern detection allows state information to circulate through a system.

Pay attention to your neighbors
Inter agent connectivity is the primary mechanism driving self-organization and emergence.

The obvious focus of the science of complex systems might seem to be prediction, but even rigorous mathematical models of complex systems are notoriously unreliable when making anything but short-term predictions. The most familiar domains in which predictions of complex systems are attempted are weather and economic forecasting. Analysis turns out to be more successful than prediction but there are other ways that scientists are applying these concepts of complex systems. A reframing of evolutionary theory in light of complex system theory has given rise to a new sub-field of computer science called adaptive computing. Rather than a programmer designing and developing an application to perform a given task, a virtual eco-system of competing programs is created and allowed to develop in parallel with fitness measured against some benchmark task such as the ability to sort numbers. John Holland formulated the concept of a genetic algorithm which was later applied by computer scientist David Jefferson and biologist Chuck Taylor.[19] Instead of writing a single program for a given task, Jefferson and Taylor creat populations of programs that run in parallel, each with the ability to reproduce themselves imperfectly. These programs *mutate* and learn across generations. Holland points out that an important way in which programs evolve using genetic algorithms differs from organisms evolving through natural selection. In the case of evolving software, the measure of fitness is determined by the programmer. In contrast, there is no objective measure of fitness in the real world. From *Complexity:*

> *"That shift in viewpoint is* ***very*** *important," says Holland. Indeed, evolutionary biologists consider it so important that they've made up a special word for it: organisms don't just evolve, they* ***co****evolve. Organisms don't change in an ecosystem by climbing uphill to the highest peak of some abstract fitness landscape[...] Real organisms constantly circle and chase one another in an infinitely complex dance of coevolution.*

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[19] Johnson, S. (2001) Emergence. The connected Lives of Ants, Brains, Cities, and Software. (pp 59-63). New York: Scribner

> *On the face of it, coevolution sounds like a recipe for chaos, says Holland. At the institute, Stuart Kauffman liked to compare it to climbing around a fitness landscape made of rubber, so that the whole thing deforms every time you take a step. And yet somehow, says Holland, this dance of evolution produces results that aren't chaotic at all. In the natural world it has produced flowers that evolved to be fertilized by bees, and bees that evolved to live off the nectar of flowers. It has produced cheetahs that evolved to chase down gazelles, and gazelles that evolved to escape from cheetahs. It has produced myriad creatures that are exquisitely adapted to each other and to the environment they live in. In the human world, moreover, the dance of coevolution has produced equally exquisite webs of economic and political dependencies--alliances, rivalries, customer-supplier relationships, and on and on.*[20] *(*emphases in original*)*

Another interesting application of complex systems theory has been proposed by liver pathologist Neil Theise, M.D. Theise not only studies stem cell plasticity, he is also a practicing Zen Buddhist and student of Kabbalah. He takes the concepts of complex systems theory to the realm of cell differentiation as well as metaphysics, inquiring into the nature of "thingness" and self. Using the now familiar ant colony example, Theise points out that the entities one perceives is entirely dependent on scale. From 10 feet away, one sees a colony, move to successively closer levels of examination and one sees a trail of ants, an individual ant, the cells of the ant, the atomic structure, and the sub-atomic particles at which point there is more no-thing than thing. He draws the following parallels between complex systems theory and Buddhist tenets[21]:

complex systems theory	**Buddhism**
Thingness is dependent on scale	emptiness of inherent existence
Inevitable mass extinction	impermanence
Systems depend on every member	interdependence
The fact of emergence is predictable, the nature of it is not	karmic law (cause and effect)

The parallels between complex system's bottom-up forces and the illusory nature of self central to Buddhist philosophy is revealed in unexpected places. Scientist JAS Kelso studies coordinated neural dynamics required for motor skills. In a paper on coordinated dynamics he writes, "...that spontaneous self-organizing coordination tendencies give rise to agency; that the most fundamental kind of consciousness, the awareness of self, springs from the ground of

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[20] Waldrop, M.M. (1992) Complexity, The emerging science at the edge of order and chaos (pp. 259). New York: Simon & Schuster

[21] Theise, N.D. (2009). Who are We? Biology in light of Complexity Theory and Contemplative Practice. Retrieved on January 12, 2009 from powerpoint presentation delivered at Upaya Zen Brain Retreat: http://www.slideshare.net/neiltheise/upaya-zen-brain-retreat-2009-presentation

spontaneous self-organized activity."[22] In his book, *Dynamic Patterns, The Self-Organization of Brain and Behavior,* Kelso writes, "the system organizes itself, but there is no 'self,' no agent inside the system doing the organizing."[23] It's in these areas of application that complex system takes on relevance to individuals, sensing and acting, learning and making decisions.

Simple observations made via our senses provide our only source of information regarding our surroundings. These sensory signals fuel the connective machinery of our brains, the main mission of which is to keep us safe and fed. One of the primary ways in which the needs of food and safety are met is through the detection of patterns... enormous, mind-boggling numbers of patterns that would render us mentally paralyzed if we had to chunk through them consciously. As luck would have it, our pattern-matching faculties hum along incessantly, as if on auto-pilot, through every minute of every day (even while we sleep - maybe even *especially* while we sleep). Pattern recognition could be said to be a lynchpin in the mechanism of learning. In fact everything we ever learned emerged out of this pattern-recognition mechanism. Some things are so obvious to our brains that we need only be exposed to them once to establish the pattern - hot things burn. This particular pattern and many others can easily be articulated as a declarative statement in plain language but the internalization of a pattern/fact/belief is not established linguistically, it is established viscerally and the resulting neuronal connection is seemingly indelible.

At their most basic, the patterns are simple valence assignments: fire bad, chocolate good, but this simplistic assignment of valence leaves out a key aspect of learning--the enaction of our relationship in the particular pattern: touching fire is bad, cooking food on fire is good, eating chocolate is good, getting chocolate on a white shirt is bad. The patterns of our relationships to external entities, ideas, tasks, and events gets ever more sophisticated and are built up much like the nesting of successive hierarchical self-organizing systems. The information we acquire is integrated and later used to build up more complicated perceptions. The difference between a sensation of physical pain and one of emotional pain might well represent different levels of integration of the same afferent signals.[24, 25] Of course, some physical, emotional, and mental experiences percolate up into conscious awareness and become *facts we know* and *things we believe*.

We often think of learning only as the establishment of these facts and as something we must do intentionally if not consciously. We may have learned a lesson *the hard way*, through some pain and suffering that quite possibly could have been avoided, but we often don't consider that

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[22] Kelso, J.A.S. (2002) The Complementary Nature of Coordination Dynamics: Self-organization and Agency (pp. 370) Nonlinear Phenomena in Complex Systems 5(4), 364-371.

[23] Kelso, J.A.S. (1995) Dynamic Patterns, The Self-Organization of Brain and Behavior (pp. 8). Cambridge, MA: MIT Press.

[24] Craig, A.D. (2003). PAIN MECHANISMS: Labeled Lines Versus Convergence in Central Processing. The Annual Review of Neuroscience 26. 1-30.

[25] Craig, A.D. (2002). How do you feel? Interoception:the sense of the physiological condition of the body. Nature Reviews, Neuroscience 3. 655-666.

we've actually *learned* something unless we are conscious of it and further, until we can clearly articulate it. In fact, learning is innate and continuous. It is dynamic and recursive. We build up ways of learning, effectively *learning how to learn*, but the nature of neuronal connectivity implies that we simply can't help but learn. We learn from the bottom-up. The process of a brain self-organizing and the process of learning are one and the same. The ability is not unique to humans or even to animals with central nervous systems. It emerges spontaneously from the faculty of sensation and its circular connection to action. This sensorimotor way of being in the world is illustrated by the following example given by Evan Thompson in his book *Mind in Life,* in which he describes the process in a single-celled organism.

> *The cells tumble about until they hit upon an orientation that increases their exposure to sugar, at which point they swim forward, up-gradient, toward the zone of greatest sugar concentration. This behavior occurs because the bacteria are able to sense chemically the concentration of sugar in their local environment through molecular receptors in their membranes. They are able to move forward by rotating their flagella in coordination like a propeller. These bacteria are, of course, autopoietic* [self-organizing]. *They also embody a dynamic sensorimotor loop: the way they move (tumbling or swimming forward) depends on what they sense, and what they sense depends on how they move.*[26]

These same single-celled organisms will move away from toxic substances. This faculty of establishing patterns of *meaning* is inextricable linked to evolution and survival. If an organism is unable to establish some sort of knowing that distinguishes safe from dangerous engagement with its environment, it will perish long before it's had a chance to reproduce. Even if one chooses to say it is not cognitive in the case of a single-celled organism, it can be argued that a learned pattern is a kind of *intelligence* in that it allows an organism to move forward into ever more successful ways of safely engaging with its environment to meet its needs. In fact, the origin of the word intelligence is the latin word *intelligere* from *inter*: **between** combined with *legere*: **choose, pick out, read**. In other words, to *choose between* or discern. It is intelligence that guides action which, in turn, provides new intelligence, ad infinitum. Sensing + valence = intelligence. Right on up the chain of evolutionary complexity, this sensorimotor circular interaction is the fundamental mode of being alive. Though I've followed the conventional pattern of temporal ordering which places sensory before motor, implying that sensation must come before action, in fact, the converse is true, the ramifications of which are far-reaching. As Kelso writes,

> *Think, for example, what happens when human embryos develop - 'Im Anfang war die Tat', as Goethe said - in the beginning was the act. In the embryo, motorneurons appear well before their sensory counterparts as Viktor Hamburger and others have shown many years ago. The elementary spontaneous movements we are born with consist of a large repertoire of spontaneous (thus self-organized) movements - making a fist, kicking, sucking, etc. etc. Only at some point does the child realize - through his own movements*

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[26] Thompson, E. (2007). Mind in Life. Biology, Phenomenology, and the Sciences of Mind (pp. 157). Harvard University Press (2007).

> *and the sensations they give rise to - that these movements are his own. If one attaches a string to his foot, he comes to realize that it is his kicking movements that are causing the mobile to move in ways that he likes. The pre-existing repertoire enables activities to happen before we make them happen. Spontaneous (self-organized) coordination tendencies thus lie at the origins of conscious agency. They are, in the words of the philosopher Maxine Sheets-Johnstone, "the mother of all cognition", presaging every conscious mind that ever said "I". From spontaneous self-organized behavior emerges the self - "I am" "I do" and from there a huge range of potentialities ('I can do'). "I-ness" arises from spontaneity, and it is this "I" that directs human action.*[27]

A vexing question arises regarding the self-organizing establishment of patterns of behavior and adaptation of the organism: if the creation of patterns of association are made so indelibly, how does one have any hope of *undoing* an established pattern? As anyone who has tried to change a long-standing habit can attest to, a pattern once established can be painfully difficult to *disconnect*. Why would this be the case? If our brains are so hard-wired to detect patterns, why is it that some of our own behavioral patterns seem blatantly obvious to those around us but remain opaque to us alone? The ability to recognize and unlearn behavioral patterns is an undeniably valuable skill, especially salient in cases of dysfunctional or addictive behavior. These questions raise issues free will and volition. In *Emergence*, Johnson addresses this issue:

> *An important distinction must be drawn between ant colonies and cities, though, and it revolves around the question of volition. In a harvester ant colony, the individual ants are relatively stupid, following elemental laws without anything resembling free will. As we have seen, the intelligence of the colony relies on the stupidity of its component parts: an ant that suddenly started to make decisions about, say, the number of ants on midden duty would be disastrous for the overall group.*[28]

In light of the deeply nested self-organizing systems that make up us humans, its interesting to consider our persistent and deep-seated sense of agency. Our higher cognitive abilities such as self-awareness and even our awareness *of* our own awareness (meta-awareness) are emergent properties. Studies examining human behavior and decision-making leave little doubt that our actions are easily influenced by environmental cues of which we remain entirely unconscious. One example was described in a New York Times article on subconscious priming:

> *...in 2005, Dutch psychologists had undergraduates sit in a cubicle and fill out a questionnaire. Hidden in the room was a bucket of water with a splash of citrus-scented cleaning fluid, giving off a faint odor. After completing the questionnaire, the young men and women had a snack, a crumbly biscuit provided by laboratory staff members.*

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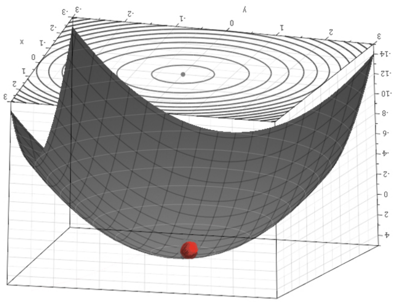
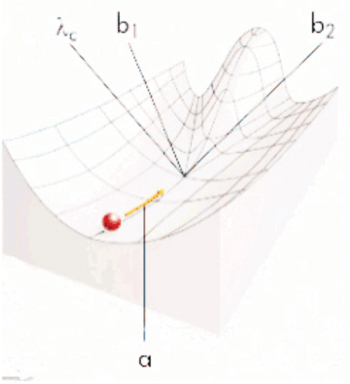
[27] Kelso, J.A.S. (2002) The Complementary Nature of Coordination Dynamics: Self-organization and Agency (pp. 370) Nonlinear Phenomena in Complex Systems 5(4), 364-371.

[28] Johnson, S. (2001) Emergence. The connected Lives of Ants, Brains, Cities, and Software. (pp 97). New York: Scribner

> *The researchers covertly filmed the snack time and found that these students cleared away crumbs three times more often than a comparison group, who had taken the same questionnaire in a room with no cleaning scent. "That is a very big effect, and they really had no idea they were doing it," said Henk Aarts, a psychologist at Utrecht University and the senior author of the study.*[29]

Knowing that we are influenced largely by unconscious environmental cues does little to inform the processes of behavioral change. If our decision-making processes are guided by a global conglomeration of conscious and unconscious homeostatic forces, we too are moving through a sort of rubber-floored fitness landscape of homeostasis which is not only deforming with each decision, but in which it's quite easy to become trapped in local areas of equilibrium. Picture a three dimensional terrain map, the vertical axis of which represent the energy level of an organism. As in nature, the system, in this case a person, moves to the lowest available energy level not unlike a marble rolling down a hill. It's easy to imagine local minima where we could become stuck, at least temporarily. The saving grace in the scenario is that the landscape is continuously changing, even in the absence of willful acts. Stasis is simply not an option for a living organism, even those that aspire to remain in the passive state of equilibrium, choosing not to act. Ultimately a decision point will arrive, a *bifurcation* in the terminology of complex systems, and though it might not be clear which path leads to the greenest pastures (i.e. low lowest valleys of energetic equilibrium), a decision is forced nonetheless. These two landscapes are shown in the following diagrams, the left topology representing a simple scenario of a local minimum, the right illustrating a bifurcation point indication a decision point and a change.





Questions surrounding self-organizing systems, volition, and decision-making become even more interesting when viewed through the perspective of individual stories. What was it that led Deborah Gordon to spend decades studying harvester ants? What compelled Neil Theise to spend several years of his life determining the size of liver bile duct cells (a determination that led to his discovery of adult stem cell plasticity)? Why was Brain Arthur obsessed with patterns of positive feedback in economic systems? While the field of cognitive science has made use of the tools of complex systems theory, it appears as though they are currently applied exclusively to

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[29] Carey, B. (2007) Who's Minding the Mind? Retrieved March 15, 2009, from the New York Times: http://www.nytimes.com/2007/07/31/health/psychology/31subl.html

machine learning and decision-making. The concept of self-organization has scarcely been applied to human behavior and higher cognitive functions such as learning, decision-making, attention, and executive function. One intriguing foray into this domain is mentioned by Kelso in his paper on coordinated dynamics. In it he states that:

> *...information can then guide, modify and direct the system's dynamics. That too has been amply demonstrated in studies of intentional change, environmental change, learning and so forth. A number of years ago, for example, it was demonstrated both empirically and theoretically that an intentional goal - as memorized information - acts in the same informational space as the coordination dynamics.*

It's not clear what is meant by "information space" but it would appear to suggest that the internalization of an intention can influence behavior, an intriguing prospect that deserves further investigation. Scientists such as Kelso and Theise sound almost philosophical about complex systems theory. Neil Theise could be described as a mystic scientist, seeing no dichotomy between his study of Kabbalah, his practice of Zen meditation, and his work as a scientist. Each of this areas are simply domains in which he seeks truth and as such, they ought to reveal no contradictions. He describes it here:

> *In our modern times, these two approaches are divided between investigational sciences and spiritual practices, modes of exploration that are now often understood as not only socially, ethically and politically separate, but even antagonistic. At best, for spiritually inclined scientists and scientifically inclined spiritual seekers, it is safest to say that these approaches are complementary, but certainly not identical.*
>
> *Yet this division is strange. After all, if scientists and contemplatives both are evaluating the True Nature of reality, how is it that we have two True Natures, rather than one?*[30]

Kelso appears to have non-dual leanings as well though he is not as revelatory in his writing. He has written a book on paradox in nature and science called *Complimentary Nature* in which he suggests that paradox must be embraced to gain a full understanding of any domain, a decidedly non-dual stance. The principles of self-organization and emergence lend themselves to a bridging of science and... what? If not god than at least the forces of order or unity. It's a delicate matter to determine what can reliably be placed opposite the word science, but heartening to discover there are scientist grappling with the prospect that science is not the only measure of truth. It will be interesting to see the ways in which the concepts of complex systems theory move into the popular mindset and how its models can be applied to the understanding of human behavior as well as larger philosophical questions.

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[30] Theise, N.D. (n.d.) Kabbalah and Complexity: Two routes to one reality (pp. 1). Retrieved January 11, 2009, from Neil D. Theise, MD: http://www.neiltheise.com/pdfs/Comp-Kablah.pdf