Complex Adaptive Systems

Serena Chan
ESD.83 Research Seminar in Engineering Systems
October 31, 2001/November 6, 2001

1 Introduction

Complexity theory is a relatively new field that began in the mid-1980s at the Santa Fe Institute in New Mexico. Work at the Santa Fe Institute is usually presented as the study of Complex Adaptive Systems (CAS). The CAS movement is predominantly American, as opposed to the European "natural science" tradition in the area of cybernetics and systems. Like in cybernetics and systems theory, CAS shares the subject of general properties of complex systems across traditional disciplinary boundaries. However, CAS is distinguished by the extensive use of computer simulations as a research tool, and an emphasis on systems, such as markets or ecologies, which are less integrated or "organized" than the ones studied by the older tradition (e.g., organisms, machines and companies).

1.1 What is Complexity?

Complexity results from the inter-relationship, inter-action and inter-connectivity of elements within a system and between a system and its environment. Murray Gell-Mann, in "Complexity" Vol. 1, No. 5, 1995/96, traces the meaning of complexity to the root of the word. *Plexus* means braided or entwined, from which is derived *complexus* meaning braided together, and the English word "complex" is derived from the Latin. Complexity is therefore associated with the intricate inter-twining or inter-connectivity of elements within a system and between a system and its environment.[1]

1.2 What are Complex Adaptive Systems?

Many natural systems (e.g., brains, immune systems, ecologies, societies) and increasingly, many artificial systems (parallel and distributed computing systems, artificial intelligence systems, artificial neural networks, evolutionary programs) are characterized by apparently complex behaviors that emerge as a result of often nonlinear spatio-temporal interactions among a large number of component systems at different levels of organization.[2] These systems have recently become known as Complex Adaptive

[1] Eve Mitleton-Kelly, "Organisations as Co-evolving Complex Adaptive Systems," British Academy of Management Conference, 1997.

[2] Dr. Vasant Honavar, Complex Adaptive Systems Group at Iowa State University, http://www.cs.iastate.edu/~honavar/alife.isu.html, (date accessed: October 28, 2001).

Systems (CAS). The theoretical framework is based on work in the natural sciences studying CAS, e.g., physics, chemistry, biology). The analysis of CAS is done by a combination of applied, theoretical and experimental methods (e.g., mathematics and computer simulation).

CAS are dynamic systems able to adapt *in* and evolve *with* a changing environment. It is important to realize that there is no separation between a system and its environment in the idea that a system always *adapts to* a changing environment. Rather, the concept to be examined is that of a system *closely linked with* all other related systems making up an ecosystem. Within such a context, change needs to be seen in terms of *co-evolution with* all other related systems, rather than as *adaptation to* a separate and distinct environment.

2 History and Origins: Intellectual Figures

The Santa Fe Institute (SFI) is a private, non-profit, multidisciplinary research and education center. Since its founding in 1984, SFI has devoted itself to creating a new kind of scientific research community, pursuing emerging science by providing multidisciplinary collaborations among visiting and residential scientists from the physical, biological, computational and social sciences. There are numerous scientists contributing to the field of complex adaptive systems. Due to time and space limitations, the following focuses on a few of the more well-known scientists and their contributing work.

<u>Murray Gell-Mann</u>

Murray Gell-Mann is Co-Chairman of the Science Board of the Santa Fe Institute and author of the popular science book *The Quark and the Jaguar: Adventures in the Simple and the Complex*. He was the Nobel laureate in physics in 1969 for his work on the theory of elementary particles. He currently focuses on complex adaptive systems.

<u>John Holland</u>

John Holland is the founder of the domain of genetic algorithms. Generic algorithms are parallel, computational representations of the processes of variation, recombination and selection on the basis of fitness that trigger most processes of evolution and adaptation. They have been successfully applied to general problem solving, control and optimization tasks, inductive learning (e.g., classifier systems), and the modeling of ecological systems (e.g., the ECHO model).

Stuart Kauffman

Stuart Kauffman is a biologist who has tried to understand how networks of mutually activating or inhibiting genes can give rise to the differentiation of organs and tissues during embryological development. His work has led him to investigate the properties of Boolean networks of different sizes and degrees of connectedness. He proposes that the self-organization displayed by such networks of genes or chemical reactions is a vital factor in evolution, corresponding to Darwinian selection by the environment.

Ilya Prigogine

Ilya Prigogine, a Nobel laureate chemistry in 1977 for his contributions to non-equilibrium thermodynamics, has studied the theory of dissipative structures. His work on dissipative structures have stimulated many scientists throughout the world and may have profound consequences for our understanding of biological systems. Prigogine aims for a better understanding of the role of time in the physical sciences and in biology. He has contributed significantly to the understanding of irreversible processes, particularly in systems far from equilibrium

Brian Goodwin

Brian Goodwin is a professor of biology in England and a member of the Board of Directors at the Santa Fe Institute. His work has been in ‘new’ biology – biology, in the form of an exact science, of complex systems dealing with dynamics and emergent order.

3 Attributes of CAS

The definition for complex adaptive systems seems to change with the different attempts at application. In order to make a good match between a hard-to-solve problem and a complexity approach, it is important to consider whether and how the problem exhibits attributes of a complex adaptive system. Research is indicating that CAS have a number of characteristics which are described in the following subsections.

3.1 Distributed Control

There is no single centralized control mechanism that governs system behavior. Although the inter-relationships between elements of the system produce coherence, the overall behavior usually cannot be explained merely as the sum of individual parts

3.2 Connectivity

As noted earlier, complexity results from the inter-relationship, inter-action and inter-connectivity of the elements within a system and between a system and its environment. This implies that a decision or action by one part within a system will influence all other related parts but not in any uniform manner.

3.3 Co-evolution

With co-evolution, elements in a system can change based on their interactions with one another and with the environment. Additionally, patterns of behavior can change over time. In 1993, Stuart Kauffman described co-evolution with his concept of fitness landscapes. The fitness landscape for a particular system, X, consists an array of all possible survival strategies available to it. As shown in Figure 1, the landscape comprises of many peaks and valleys. The higher the peak, the greater the fitness it represents. The evolution of X can be thought of as a voyage across the fitness landscape with the goal of locating the highest peak. X can get stuck on the first peak it approaches if the strategy is incremental improvement. If X changes its strategy, other interconnected systems will respond and the landscape will undergo some change.

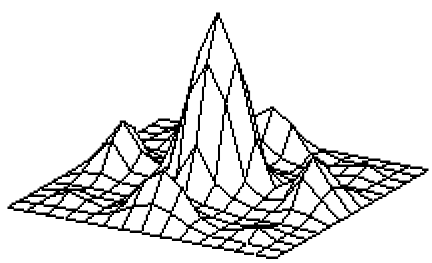

Figure 1. Fitness landscape.

3.4 Sensitive Dependence on Initial Conditions

CAS are sensitive due to their dependence on initial conditions. Changes in the input characteristics or rules are not correlated in a linear fashion with outcomes. Small changes can have a surprisingly profound impact on overall behavior, or vice-versa, a huge upset to the system may not affect it. Starting in the 1960s, Edward Lorentz, an American physicist, studied the solutions to equations describing weather patterns. His goal was to find a long-term weather forecast. With the aid of a computer, he traced out the solutions on a screen, as shown in Figure 2, and realized that he was dealing with a radically new type of behavior pattern. Very small changes in initial conditions in the weather system can lead to unpredictable consequences, even if everything in the system is causally connected in a deterministic way. The current state of the weather is no predictor of what it will be in a couple of days time because tiny disturbances can produce exponentially divergent behavior.

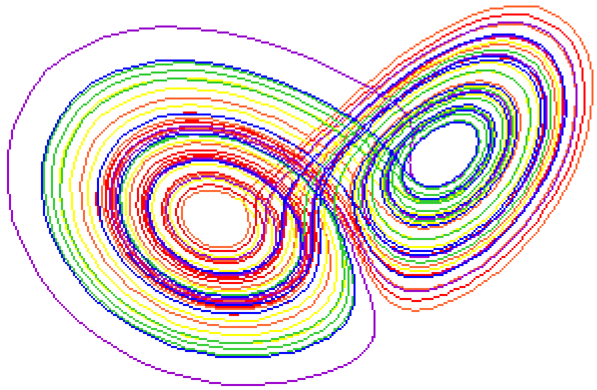

Figure 2. Lorentz solution: two attractor graph.

The consequences of Lorentz's mathematical discovery are profound. Because most natural processes are at least as complex as the weather, the world is fundamentally unpredictable. This means the end of scientific certainty, which is a property of "simple" systems (e.g, the ones used for electric lights, motors and electronic devices). Real systems, especially living organisms, are fundamentally unpredictable in their behavior. Long-term prediction and control are therefore believed to not be possible in complex systems.

3.5 Emergent Order

Complexity in complex adaptive systems refers to the potential for emergent behavior in complex and unpredictable phenomena. Examples of complex adapting systems include the economy, ecosystems, the human brain, developing embryos and ant colonies. Each is a system with a network of many agents acting in parallel. In an economy, the agents might be individuals or households. In an ecosystem, the agents are species. In a brain, the agents are nerve cells. In an embryo, the agents are cells. In each system, each agent is in an environment produced by its interactions with the other agents in the system. There is constant action and reaction to what other agents are doing, thus nothing in the environment is essentially fixed.

From the interaction of the individual agents arises some kind of global property or pattern, something that could not have been predicted from understanding each particular agent. For example, in the brain, consciousness is an emergent phenomenon, which comes from the interaction of the brain cells. Global properties result from the aggregate behavior of individuals. Furthermore, the control of a complex evolving system tends to be highly dispersed. There is no cell within a developing embryo, nor a master neuron in the brain. The overall behavior observed in the economy is a result of the countless decisions made by millions of individual people. Any coherent behavior in a system arises from competition and co-operation among the agents themselves.

For many years, the second law of thermodynamics - that systems tend toward disorder - has generally been accepted. Ilya Prigogine's work on “dissipative structures” in 1977 showed that this was not true for all systems. Some systems tend towards order not disorder and this is one of the big discoveries in the science of complexity. Kauffman uses computer simulations of CAS demonstrate that it is possible for the order of new survival strategies to emerge from disorder through a process of spontaneous self-organization.

Order can result from non-linear feedback interactions between agents where each agent goes about his own business. Emergent behavior can be easily seen in the flocking behavior of birds. Research using computer simulations has shown that one can model the flocking behavior of birds by using a few simple rules such as the distance each bird maintains between itself and other birds and other objects. These rules are entirely local to each bird. There is no explicit rule to form a flock. If a flock does form, it would have done so from the bottom up, as an emergent phenomenon. Indeed, flocks did form every time the simulation was run. Thus, it appears that self-organization is an inherent property of CAS.

3.6 Far From Equilibrium

In 1989, Nicolis and Prigogine showed that when a physical or chemical system is pushed away from equilibrium, it could survive and thrive. If the system remains at equilibrium, it will die. The “far from equilibrium” phenomenon illustrates how systems that are forced to explore their space of possibilities will create different structures and new patterns of relationships.

This concept is being explored in medical cardiology, in the study of normal and abnormal heartbeat patterns. The rhythmic beating of the heart is very orderly but there exists a subtle but apparently fundamental irregularity. The interval between heartbeats varies in a disorderly and unpredictable manner in healthy individuals, particularly in young children. Regularity of the heartbeat interval is a sign of dinger – order in heart dynamics indicates insensitivity and inflexibility. Therefore, it can be said that complex adaptive systems function best when they combine order and chaos in an appropriate measure.

3.7 State of Paradox

Other research in complex adaptive systems has indicated dynamics combining both order and chaos. This reinforces the idea of bounded instability or the edge of chaos that is characterized by a state of paradox: stability and instability, competition and cooperation, order and disorder.

4 Tools for CAS

4.1 Aggregation of Model

Aggregation of models of complex systems is useful for studying CAS because aggregation simplifies the model without introducing significant error. Describing general CAS via Markov chains is the most general too. Markov chains are used to describe various system states and their relationships. Other tools that perform aggregation are simple evolutionary algorithms with selection and mutation, with fitness functions.

4.2 Test Problem Generation

Another set of tools for studying CAS is known as "test problem generators." Many CAS run in an environment, for example, evolutionary algorithms run within an environment of a fitness function. Various ad hoc environments are often created in order to understand the behavior of these systems. Generators can produce random environments with varying minor adjustments. The goal is to match algorithm performance with environmental attributes.

4.3 Agent-based Simulation

Agent-based simulation is a technique that serves as a platform for imitating the nonlinear characteristics of real-world complex systems. Among the dominant forms of modeling in the social sciences today is game theory, which is built on rational choice assumptions. Agent-based modeling is an alternative method most suitable when the system to be studied exhibits adaptive behavior.

5 Evaluation: Application of CAS to Engineering Systems

Although it has been mentioned that CAS can include artificial systems such as parallel and distributed computing systems, artificial intelligence systems and artificial neural networks, there is relatively little research on the application of CAS to engineering systems. It appears that complexity theory doesn't really apply to engineering systems. One may believe that the Internet can be characterized as a complex adaptive system, in its ability to re-route packets if a link is known to be congested or off-line. However, the Internet is does not exhibit any emergent behavior. While the Internet is a large complex system, the routing of packets is a chosen engineering design. People have developed the thinking that is behind the system. The Internet does not exhibit behavior that is surprising, i.e., not programmed. Thus, the basic question in applying CAS to engineering systems appears to be: can one design artifacts with emergent behavior (i.e., not pre-programmed behavior)?

6 Conclusions

The field studying CAS is young and thus not very well established yet. Researchers investigate the processes by which systems, consisting of many interacting components, change their structure in response to external or internal pressures. As such, these systems create novelty, self-organize, evolve, and adapt to a changing environment, usually generating more complexity in the process. These investigations are spread over nearly all the traditional disciplines: mathematics, physics, chemistry, biology, psychology, economy, computer science, etc. There are numerous publications, by authors working in different disciplines, spread over hundreds of journals and books. This makes it difficult for people newly entering the domain to get a complete overview of the existing body of knowledge. The following subsection recommends several resources for the reader to learn more about CAS and its application in many different areas of study.

6.1 Resources for Further Interest

There are numerous popular science books written about complexity and complex adaptive systems. Mitchell Waldrop, a science writer, and Murray Gell-Mann offer good reviews of the main ideas underlying the CAS approach. John Casti, a systems analyst and another Santa Fe collaborator, has written several popular science books, discussing different issues in the modeling of complex systems, - integrating insights from the CAS approach with the older traditions. Below is a brief listing of some general resources to peruse:

Gleick, James. (1998) *Chaos*.

Goodwin, Brian. (1994) *How the leopard changed its spots.*

Kauffman, Stuart. (1995) *At home in the universe*.

Lewin, Roger. (1993) *Complexity: Life on the edge of chaos.*

Miller, D. (1990) *The Icarus paradox: How excellent organizations can bring about their own downfall.*

Nicolis G. and Prigogine I. (1989) *Exploring complexity.*

Prigogine, Ilya. (1977) “Order through fluctuations: self organisation and social system” in Jatsch and Waddington, *Evolution and consciousness: human systems in transition*.

Stacey, Ralph. (1996) *Complexity and creativity in organizations.*

Waldrop, Mitchell. (1992) *Complexity: The emerging science at the edge of order and chaos*.

http://www.brint.com/Systems.htm

http://www.casresearch.com/

http://www.lse.ac.uk/LSE/COMPLEX/publications.htm

http://www.santafe.edu/

References

http://www.santafe.edu/ (Date accessed: October 29, 2001).

http://www.cs.uwyo.edu/~wspears/theory.html (Date accessed: October 29, 2001).

http://www.cs.iastate.edu/~honavar/alife.isu.html (Date accessed: October 29, 2001).

http://pespmc1.vub.ac.be/CAS.html (Date accessed: October 29, 2001).

http://www.econ.iastate.edu/tesfatsi/caswork.htm (Date accessed: October 29, 2001).

http://www.trojanmice.com/articles/another.htm (Date accessed: October 29, 2001).

http://bprc.warwick.ac.uk/comp.html (Date accessed: October 29, 2001).

Kauffman, Stuart *Origins of order: self organisation and selection in evolution*. Oxford University Press, 1993.

Mitleton-Kelly, Eve. “Organisations as Co-evolving Complex Adaptive Systems.” British Academy of Management Conference 1997.

Prigoginem Ilya. and Stengers, Isabelle. *Order out of chaos: man’s new dialogue with nature*. Bantam Books, 1984.