GENERAL FEATURES OF COMPLEX SYSTEMS

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Summary

From biochemical reactions to global development, complexity has arisen as a unifying feature of our world. In this arena of complex systems, new approaches are central to advancing our understanding and capabilities. These approaches include recognizing the importance of patterns of behavior; the space of possibilities; and adaptive processes that select effective behaviors for a complex world. As a discipline, complex systems is

a new field of science studying how parts of a system and their relationships give rise to the collective behaviors of the system, and how the system interrelates with its environment. Social systems formed (in part) out of people, the brain formed out of neurons, molecules formed out of atoms, the weather formed out of air flows are all examples of complex systems. The field of complex systems cuts across all traditional disciplines of science, as well as engineering, medicine and management.

The excitement of scientists as well as the public about this new field reflects its potential impact on our ability to understand questions that affect everyday life, perspectives on the world around us, fundamental philosophical disputes, and issues of public concern including major societal challenges, the dynamics of social networks, the Internet and the World Wide Web, biomedical concerns, psychology, ecology and global development.

In this article we introduce concepts and key insights that guide our understanding of complex systems. We explain these concepts using simple discussions of fads, panics and cliques, and how memory and creativity works. We describe the interplay of collaboration and competition, and the origin of altruism and selfishness. We discuss the role of control in human organizations and how the growing complexity of human civilization is accompanied by a shift from central to distributed control leading to a transition no less important than the industrial revolution.

1. Overview

1.1. Parts, Wholes and Relationships

In the last few years the obscurity of science has been shattered by a new approach which touches on many immediate and current problems we care about: how our minds work, how family relationships work, how to organize a business, how society works, how the environment can be protected, how to improve medical care, how effective third world development can be achieved. While scientists continue to learn and debate the opportunities that this new approach can yield, many people, both scientists and non-scientists, are reveling in the new perspectives and insights being gained. This guide is an introduction to the simple and powerful perspectives of "complex systems". To understand why this approach can do so much that is new, we have to recognize the strengths and weaknesses of how science has previously approached understanding the world around us.

Scientists look at something and want to understand how it does what it does. One of the most important observations is that everything is made of parts. So, reasonably enough, we say, let's figure out how its parts work; this will help us know how it works. When we look at one of the parts, we realize that it too is made of parts. The next step is to look at the parts that make up the part. This progresses until we have often forgotten what it was that we were trying to do in the first place. The human body is formed out of nine organ systems; these organ systems are formed of organs, which are formed of tissues, which are formed of cells, which are formed of organelles, which are formed of molecules, which are formed of atoms, which are formed of elementary particles. The same types of molecules form all biological systems. The same types of particles form all matter, living and nonliving. These are powerful and surprising insights that, today, are taken for granted by scientists. Trees and rocks are made of the same building blocks. Physicists take this for granted. People and trees are made of the same building blocks. Biologists take this for granted. Therefore, physicists consider the study of elementary particles to be the study of all of nature. Biologists consider the study of biological molecules to be the study of all life. Science has made great progress by taking things apart. What is left out of this approach is the problem of understanding relationships between the parts. The science of parts has helped us understand the world around us. It is becoming increasingly clear, however, that many important questions can only be addressed by thinking more carefully about relationships. Indeed one of the main problems in answering questions or solving problems is that we think the problem is in the parts, when it is really in the relationships between them.

Scientists generally think that the parts are universal, but the way parts work together is specific to each system. In recent years it has become increasingly clear that how parts work together can also be studied in general and by doing so we gain insight into every kind of system that exists --physical systems like the weather, as well as biological and social systems.

"Complex Systems" is the new approach to science studying how relationships between parts give rise to the collective behaviors of a system, and how the system interacts and forms relationships with its environment. Social systems formed (in part) out of relationships between people, the brain formed out of neurons, molecules formed out of atoms, the weather formed out of air flows are all examples of complex systems. Studying complex systems cuts across all of science, as well as engineering, management, and medicine. It is also relevant to art, history, literature and other humanities. It focuses on certain questions about relationships and how they make parts into wholes. These questions are relevant to all systems that we care about.

There are three interrelated approaches to the modern study of complex systems; (1) how interactions give rise to patterns of behavior, (2) the space of possibilities, and (3) the formation of complex systems through pattern formation and evolution. There are many advances that have made complex systems an exciting area of research today. It is impossible to discuss all of them here, but the taste provided here will hopefully invite further inquiry.

To start things off, in the next two short sections, which are part of the overview, we will introduce the concepts of emergence and interdependence. Sections 2-4 describe each of the three approaches mentioned above.

The second section is about how patterns of behavior arise from interactions. Simple models of local influences give rise to self-organized patterns. Models of influences in more complex networks can be used to study the patterns of behavior of neurons in the brain, or more complex patterns of social behavior. Using these patterns the network structure of the brain can be related to properties of mind. Similar ideas apply to other networks, including social networks.

The third section is about describing complex systems and the way complexity and scale are balanced against each other. Here, the word scale is used just as in phrases like "economies of scale" or "scale of operation" referring to the size of the activity that is taking place.

These ideas are related to thinking about the space of possibilities—the possible patterns that can happen, not just the one that is happening.

The balance of scale and complexity will help us understand how social systems are organized and how historical changes in society are leading to a networked global society.

The fourth section is about evolution and how making incremental changes can be an effective way to explore the possibilities.

It is important to realize that the standard idea that evolution is about competition is not really complete. Cooperation and competition always work together.

1.2. Emergence

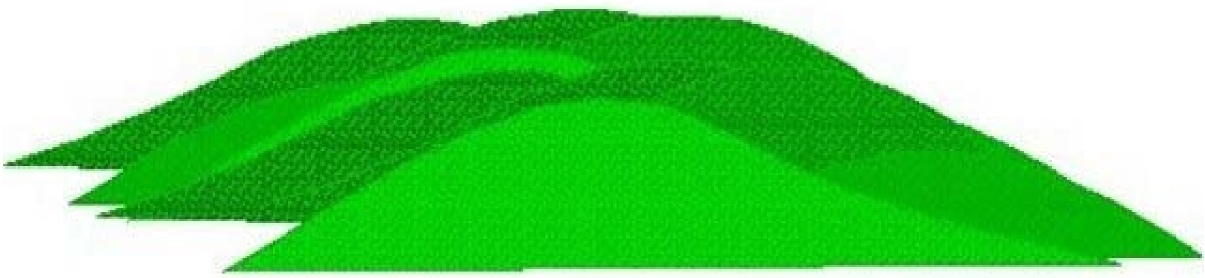

Figure 1: Forest on hills: distant view

In Figure 1 we see a forest on hills. In Figure 2 we see trees, plants and animals. The forest on the hills can be understood as being made up of many trees, animals and other plants. An old expression is "Can't see the forest for the trees".

This expression suggests that it is important to have the large-scale view, the long-range perspective. Details get in the way of having this large-scale view. Science has focused on the details, but learning about the long-range view is also important.

A forest has its own behaviors; fires and regrowth are part of the natural behavior of a forest. Of course anything that the forest does is made up of many details of what happens to trees and animals and other plants. *Emergence* refers to the relationship between the details and the larger view.

It is not about the importance of the details or the importance of the larger view; it is about the relationship between them. Specifically, which details are important for the larger view, and which are not?

Figure 2: Trees, plants, and animals in a forest: closer view

1.3. Interdependence

The study of complex systems helps us recognize and understand indirect effects. Problems that are difficult to solve by traditional approaches are often hard because the causes and effects are not obviously related. Pushing on a complex system "here" often has effects "over there" because the parts are *interdependent*. This has become more and more apparent in our efforts to solve societal problems or avoid ecological disasters caused by our own actions. The field of complex systems provides a number of sophisticated tools, some of them concepts that help us think about these systems, some of them analytical for studying these systems in greater depth, and some of them computer-based for describing, modeling or simulating these systems.

The first issue, however, is just to begin thinking about how parts of a system affect each other. If we take one part of the system away, how will this part be affected, and how will the others be affected? Sometimes the effect is small, sometimes the effect is large; and sometimes there are many effects, sometimes only a few. Consider three examples: a material, like a piece of metal or a liquid, a plant, and an animal.

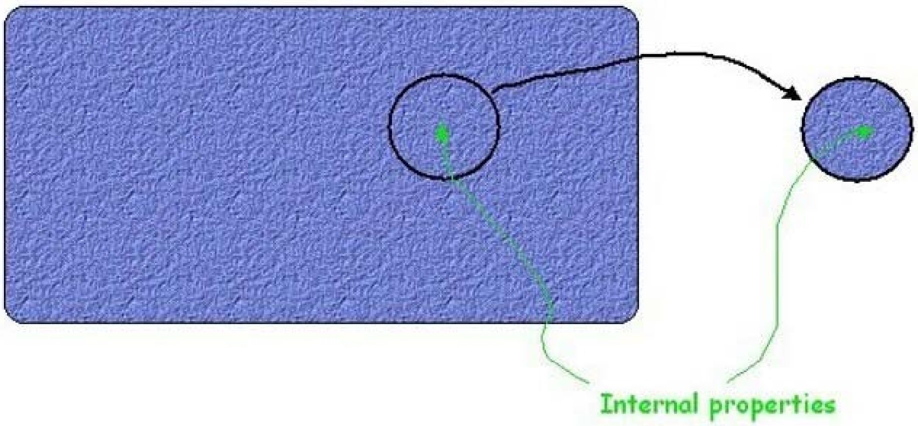

Figure 3: Effects of separation: A piece of material

For the material in Figure 3, the internal properties are not changed, the piece doesn't care, and neither does the rest of the material.

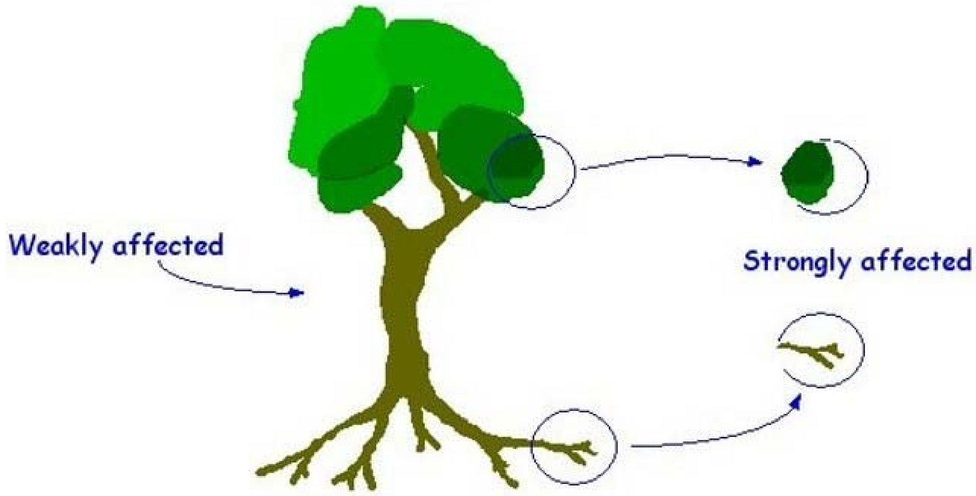

Figure 4: Effects of separation: A plant and its parts

For the plant in Figure 4, if you take a part of it away, like a branch or some roots, typically the plant will continue to grow more or less the way it would otherwise. There are exceptions, like cutting a lateral part of the trunk, but generally the plant is not strongly affected. On the other hand the part of the plant that is cut away is strongly affected. It will generally die unless it is placed in very special conditions.

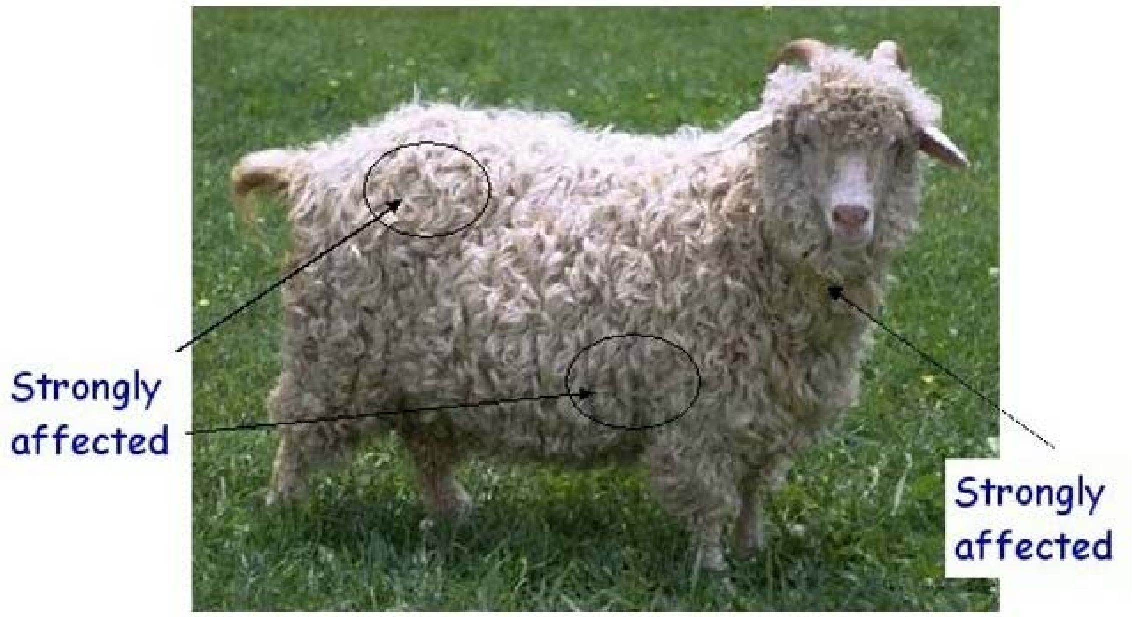

Figure 5: Effects of separation: An animal and its parts

Compare this with an animal in Figure 5. We are not talking about removing part of the wool of the sheep. Taking part of the animal away will have devastating effects both on the part and on the rest of the animal.

These three examples show very different kinds of interdependence. Recognizing that these different behaviors exist is an important part of characterizing all of the systems we are interested in. Consider the family or organization you are part of. How strong are the dependencies between the parts? What would happen if a part were taken away? Does it matter which part? These questions are key questions for understanding the system and how we might affect it by our actions.

2. Self-Organizing Patterns

2.1. What is Pattern Formation?

When people make something, like a car, they put each part in a particular place to make a specific structure that will do a specific task. When someone paints a picture, they place each patch of paint in a particular place to make the picture. In nature we notice that there are patterns that form without someone putting each part in a particular place. The pattern seems simply to happen by itself. It *self-organizes*. Sometimes these patterns are regular, like ripples of sand on a beach or in the desert (see Figure 6).

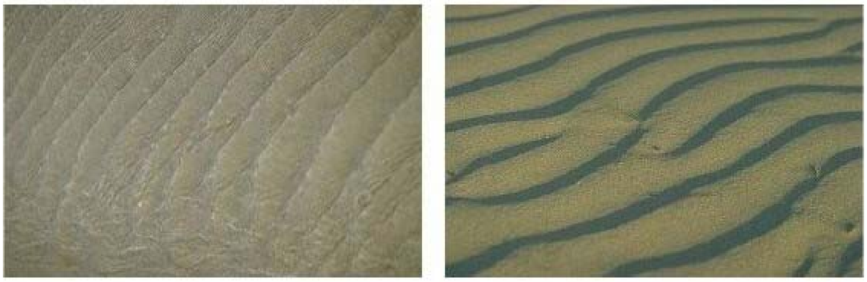

Figure 6: Patterns of sand on a beach and in the desert

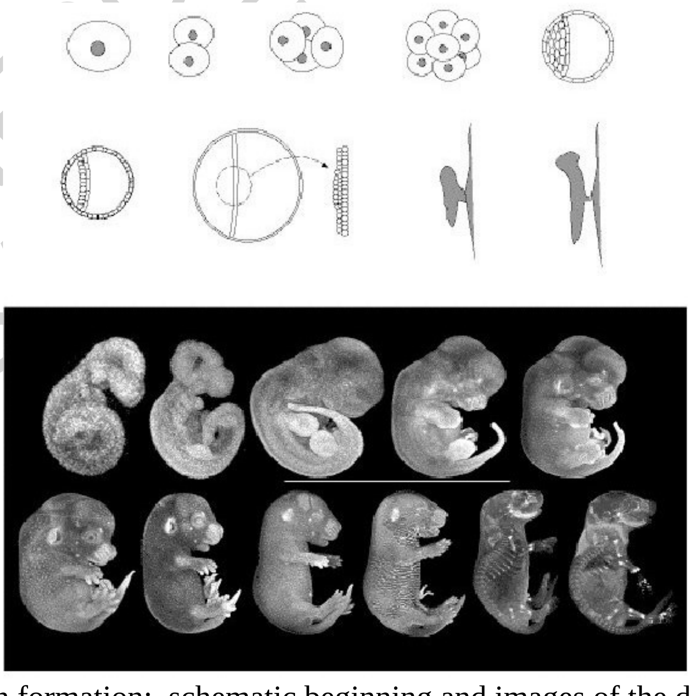

Figure 7: Pattern formation: schematic beginning and images of the development of a mouse fetus

Sometimes they are very intricate and have an intricate functioning. One of the most remarkable patterns is the human body itself, which forms from a single cell by a process of *development*.

This process is similar to the one that happens for animals, as illustrated in Figure 7 for a mouse (images courtesy of Brad Smith, Elwood Linney and the Center for In Vivo Microscopy at Duke University [A National Center for Research Resources, NIH]). The first two rows at the top are schematic drawings, the bottom two are images of developing mice.

During development, some of the cells form the heart, some form the liver, and some form the bones. There is no agent that puts each part in its place. Still, when the process is done the parts work together. How do the cells know where to go, or what form and function to take in each place?

At one time it was thought that there is a small human being in the first cell, a "homunculus" that simply grew in size. We now know that this is not correct. There is a kind of process that is in part directed by the information in the initial cell. Much of this information is found in the DNA in the nucleus of the cell. People still often call DNA a "blueprint" but this is also a mistake, just like the idea of a homunculus is a mistake. A blueprint is a picture of the structure with each part shown.

There isn't a picture of a human being there. The DNA information is not in the shape of a human being. In some way, a way we do not really understand, the DNA tells the cell how it should talk to other cells. As they talk to each other, they form the structures of the body. Imagine giving instructions to a brick, about how to talk to other bricks, walking away and coming back to find a house in place with all of the windows, plumbing and electrical systems in place. Even if we had a brick that could move around and morph into plumbing and electrical wires, it is not easy to imagine how this could be done.

As scientists, we would like to understand how this self-organizing process takes place. We would like to understand the mechanism by which patterns form. We would also like to understand how the pattern that arises is determined. This could lead to a revolution in engineering and in management. The idea is that instead of specifying each of the parts of a system we want to build, we can specify a process that will create the system that we want to make. This process would use the natural dynamics of the world to help us create what we want to make.

There is another motivation for understanding self-organizing patterns. Patterns of behavior of human beings in economic and social systems also cannot be explained directly from external forces. External forces cannot explain fads of people buying products, and price changes in stock markets where prices change dramatically from day to day or even minute to minute. Traditional economics tries to understand how behavior is related to external forces. The interactions between people are, however, important in creating fads and market panics as well as day-to-day fluctuations. These are self-organizing patterns. Without understanding how patterns arise from the interactions inside a system we cannot understand these behaviors.

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Biographical Sketch

Professor **Yaneer Bar-Yam** is founding president of the New England Complex Systems Institute. He received his Ph.D. from MIT in Physics in 1984. He was a Bantrell Postdoctoral Fellow, and a joint postdoctoral fellow at MIT and IBM. After a junior faculty appointment at the Weizmann Institute, he became an Associate Professor of Engineering at Boston University in 1991. He left Boston University in 1997 to become president of the New England Complex Systems Institute. He is also Associate of the Department of Molecular and Cellular Biology of Harvard University.

Prof. Bar-Yam studies the unified properties of complex systems as a systematic strategy for answering basic questions about the world. His research is focused both on formalizing complex systems concepts and relating them to everyday problems. In particular, he studies the relationship between observations at different scales, formal properties of descriptions of systems, the relationship of structure and function, the representation of information as a physical quantity, and quantitative properties of the complexity of real systems. Applications have been to physical, biological and social systems.

Prof. Bar-Yam has made contributions to: the theory of the structural and electronic dynamics of materials; the theory of polymer dynamics and protein folding; the theory of neural networks and structure-function relationships; the theory of quantitative multiscale complexity; and, the theory of evolution.

Prof. Bar-Yam is author of over a hundred scientific articles and the textbook *Dynamics of Complex Systems* (1997) addressing the entire field of complex systems. He is Chairman of the International Conference on Complex Systems and Managing Editor of *InterJournal* -- an on-line electronic journal. He has consulted and given courses for: the World Bank, MITRE, and the US military and intelligence communities. He has taught about complex systems in Canada, China, Columbia, France, Italy, Japan, Korea, Portugal, Russia and many places in the U.S.