What Is Complexity?

Chapter 1

Ideas thus made up of several simple ones put together, I call Complex; such as are Beauty, Gratitude, a Man, an Army, the Universe.

—John Locke, An Essay Concerning Human Understanding

Brazil: The Amazon rain forest. Half a million army ants are on the march. No one is in charge of this army; it has no commander. Each individual ant is nearly blind and minimally intelligent, but the collective whole moves with an efficiency and purpose that are clearly of great importance for the survival of the colony as a whole. Consider, for example, the use of soil, or background and history.

Nigel Franks, a biologist specializing in ant behavior, has written, "The solitary army ant is a behemoth of the forest; it has been described as an "immense" and "intelligent," and "if 100 army ants are placed on a flat surface, they will walk around in never decreasing circles until they die of exhaustion." Yet half a million of them together, and the group as a whole, becomes what some have called a superorganism, with the ability to collectively move and act as a single entity.

Such questions at the edges of complex systems, an interdisciplinary field of research that seeks to explain how large numbers of relatively simple entities organize themselves without the benefit of any central controller, into collective wholes that create patterns, use information, and, in some cases, evolve and learn. The word complex comes from the Latin root placent, to weave, entwine. In complex systems, many simple parts are irrevocably entwined, and the collective emerges from the interaction of many different fields.

Complex systems researchers assert that different complex systems in nature, such as insect colonies, immune systems, brains, and economies, have much in common. Let’s look more closely.

Insect Colonies

Colonies of social insects provide some of the richest and most mysterious examples of complex systems in nature. An ant colony, for instance, can consist of millions of individual ants, each one a rather simple creature that obeys its genetic imperatives to seek out food, respond in simple ways to the chemical signals of other ants in its colony, can attack intruders, and so forth. However, as any casual observer of the outdoors can attest, the ants in a colony, performing complex structures that are clearly of great importance for the survival of the colony as a whole. Consider, for example, their use of soil,
leaves, and twigs to construct huge nests of great strength and stability, with large networks of underground passages and dry, warm, brooding chambers whose temperatures are carefully controlled by decaying nest materials and the ants' own bodies. Consider also the long bridges certain species of ants build with their own bodies to allow emigration from one nest site to another via tree branches separated by great distances (to an ant, that is) (figure 1.1). Although much is now understood about ants and their social structures, scientists still can fully explain neither their individual nor group behavior: exactly how the individual actions of the ants produce large, complex structures, how the ants signal one another, and how the colony as a whole adapts to changing circumstances (e.g., changing weather or attacks on the colony). And how did biological evolution produce creatures with such an enormous contrast between their individual simplicity and their collective sophistication?

The Brain

The cognitive scientist Douglas Hofstadter, in his book *Gödel, Escher, Bach*, makes an extended analogy between ant colonies and brains, both being complex systems in which relatively simple components with only limited communication among themselves collectively give rise to complicated and sophisticated system-wide ("global") behavior. In the brain, the simple components are cells called neurons. The brain is made up of many different types of cells in addition to neurons, but most brain scientists believe that the actions of neurons and the patterns of connections among groups of neurons are what cause perception, thought, feelings, consciousness, and the other important large-scale brain activities.

Neurons are pictured in figure 1.2 (top). Neurons consist of three main parts: the cell body (soma), the branches that transmit the cell's input from other neurons (dendrites), and the single trunk transmitting the cell's output to other neurons (axon). Very roughly, a neuron can be either in an active state (firing) or an inactive state (not firing). A neuron fires when it receives enough signals from other neurons through its dendrites. Firing consists of sending an electric pulse through the axon, which is then converted into a chemical signal via chemicals called neurotransmitters. This chemical signal in turn activates other neurons through their dendrites. The firing frequency and the resulting chemical output signals of a neuron can vary over time according to both its input and how much it has been firing recently.

These actions recall those of ants in a colony: individuals (neurons or ants) perceive signals from other individuals, and a sufficient summed strength of these signals causes the individuals to act in certain ways that produce additional signals. The overall effects can be very complex. We saw that an explanation of ants and their social structures is still incomplete; similarly, scientists don't yet understand how the actions of individual or dense networks of neurons give rise to the large-scale behavior of the brain (figure 1.2, bottom). They don't understand what the neuronal signals mean, how large numbers of neurons work together to produce global cognitive behavior, or how exactly they cause the brain to think thoughts and learn new things. And again, perhaps most puzzling is how such an elaborate signaling system with such powerful collective abilities ever arose through evolution.

The Immune System

The immune system is another example of a system in which relatively simple components collectively give rise to very complex behavior involving signaling and control, and in which adaptation occurs over time. A photograph illustrating the immune system's complexity is given in figure 1.3.
What is complexity?

The immune system, like the brain, differs in sophistication in different animals, but the overall principles are the same across many species. The immune system consists of many different types of cells distributed over the entire body (in blood, bone marrow, lymph nodes, and other organs). This collection of cells works together in an effective and efficient way without any central control.

The star players of the immune system are white blood cells, otherwise known as lymphocytes. Each lymphocyte can recognize, via receptors on its cell body, molecules corresponding to certain possible invaders (e.g., bacteria). Some one trillion of these patrolling sentries circulate in the blood at a given time, each ready to sound the alarm if it is activated—that is, if its particular receptors encounter, by chance, a matching invader. When a lymphocyte is activated, it secretes large numbers of molecules—antibodies—that can identify similar invaders. These antibodies go out on a seek-and-destroy mission throughout the body. An activated lymphocyte also divides at an increased rate, creating daughter lymphocytes that will help hunt out invaders and secrete antibodies against them. It also creates daughter lymphocytes that will hang around and remember the particular invader that was seen, thus giving the body immunity to pathogens that have been previously encountered.
One class of lymphocytes are called B cells (the B indicates that they develop in the bone marrow) and have a remarkable property: the better the match between a B cell and an invader, the more antibody-secreting daughter cells the B cell creates. The daughter cells each differ slightly from the mother cell in random ways via mutations, and these daughter cells go on to destroy the invader. The result is a kind of Darwinian natural selection process in which the match between B cells and invaders gradually gets better and better, until the antibodies being produced are extremely efficient at seeking and destroying the culprit microorganisms.

Many other types of cells participate in the orchestration of the immune response. T cells (which develop in the thymus) play a key role in regulating the response of B cells. Macrophages roam around looking for substances that have been tagged by antibodies, and they do the actual work of destroying the invaders. Other types of cells help effect longer-term immunity. Still other parts of the system guard against attacking the cells of one’s own body. Like that of the brain and ant colonies, the immune system’s behavior arises from the independent actions of myriad simple players with no one actually in charge. The actions of the simple players—B cells, T cells, macrophages, and the like—can be viewed as a kind of chemical signal-processing network in which the recognition of an invader by one cell triggers a cascade of signals and the like. Our understanding of these systems has been greatly expanded by understanding the behavior of simpler systems described earlier in this book. For example, the behavior of ants and immune systems is emergent, in that it arises from the independent actions of the component parts (the ants and the immune cells) and the way they interact with one another. In the case of immune systems, the interactions between different types of cells and substances can lead to complex patterns of behavior that are not present in the environment and to produce new behaviors that could not have been predicted from the behavior of the individual parts.

**Figure 1.5.** Network structure of a section of the World Wide Web. (Reprinted with permission from M.E.J. Newman and M. Girvin, *Physical Review Letters E*, 69, 026113, 2004. Copyright 2004 by the American Physical Society.)

Complex behavior emerging from simple rules in the World Wide Web is currently a hot area of study in complex systems. Figure 1.5 illustrates the structure of one collection of Web pages and their links. It seems that much of the Web looks very similar; the question is, *why?*

**Common Properties of Complex Systems**

When looked at in detail, these various systems are quite different, but viewed at an abstract level they have some intriguing properties in common:

1. **Complex collective behavior**: All the systems I described above consist of large networks of individual components (ants, B cells, neurons, stock-buyers, Web-site creators), each typically following relatively simple rules with no central control or leader. It is the collective actions of vast numbers of components that give rise to the complex, hard-to-predict, and changing patterns of behavior that fascinate us.
2. **Signaling and information processing**: All these systems produce and use information and signals from both their internal and external environments.

3. **Adaptation**: All these systems adapt—that is, change their behavior to improve their chances of survival or success—through learning or evolutionary processes.

Now I can propose a definition of the term *complex system*: a system in which large networks of components with no central control and simple rules of operation give rise to complex collective behavior, sophisticated information processing, and adaptation via learning or evolution. (Sometimes a differentiation is made between complex adaptive systems, in which adaptation plays a large role, and nonadaptive complex systems, such as a hurricane or a turbulent rushing river. In this book, as most of the systems I do discuss are adaptive, I do not make this distinction.)

Systems in which organized behavior arises without an internal or external controller or leader are sometimes called self-organizing. Since simple rules produce complex behavior in hard-to-predict ways, the macroscopic behavior of such systems is sometimes called emergent. Here is an alternative definition of a complex system: a system that exhibits nontrivial emergent and self-organizing behaviors. The central question of the sciences of complexity is how this emergent self-organized behavior comes about. In this book I try to make sense of these hard-to-pin-down notions in different contexts.

### How Can Complexity Be Measured?

In the paragraphs above I have sketched some qualitative common properties of complex systems. But more quantitative questions remain: Just how complex is a particular complex system? That is, how do we measure complexity? Is there any way to say precisely how much more complex one system is than another?

These are key questions, but they have not yet been answered to anyone’s satisfaction and remain the source of many scientific arguments in the field. As I describe in chapter 7, many different measures of complexity have been proposed; however, none has been universally accepted by scientists. Several of these measures and their usefulness are described in various chapters of this book.

But how can there be a science of complexity when there is no agreed-on quantitative definition of complexity?