Dynamics of Complex Systems

Studies in Nonlinearity

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Yaneer Bar-Yam

Dynamics of Complex Systems

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This book is dedicated with love to my family

Zvi, Miriam, Aureet and Sageet

Naomi
and our children
Shlomiya, Yavni, Maayan and Taeer

Aureet’s memory is a blessing.

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Preface

"Complex" is a word of the times, as in the often-quoted "growing complexity of life." Science has begun to try to understand complexity in nature, a counterpoint to the traditional scientific objective of understanding the fundamental simplicity of laws of nature. It is believed, however, that even in the study of complexity there exist simple and therefore comprehensible laws. The field of study of complex systems holds that the dynamics of complex systems are founded on universal principles that may be used to describe disparate problems ranging from particle physics to the economics of societies. A corollary is that transferring ideas and results from investigators in hitherto disparate areas will cross-fertilize and lead to important new results.

In this text we introduce several of the problems of science that embody the concept of complex dynamical systems. Each is an active area of research that is at the forefront of science. Our presentation does not try to provide a comprehensive review of the research literature available in each area. Instead we use each problem as an opportunity for discussing fundamental issues that are shared among all areas and therefore can be said to unify the study of complex systems.

We do not expect it to be possible to provide a succinct definition of a complex system. Instead, we give examples of such systems and provide the elements of a definition. It is helpful to begin by describing some of the attributes that characterize complex systems. Complex systems contain a large number of mutually interacting parts. Even a few interacting objects can behave in complex ways. However, the complex systems that we are interested in have more than just a few parts. And yet there is generally a limit to the number of parts that we are interested in. If there are too many parts, even if these parts are strongly interacting, the properties of the system become the domain of conventional thermodynamics—a uniform material.

Thus far we have defined complex systems as being within the mesoscopic domain—containing more than a few, and less than too many parts. However, the mesoscopic regime describes any physical system on a particular length scale, and this is too broad a definition for our purposes. Another characteristic of most complex dynamical systems is that they are in some sense purposive. This means that the dynamics of the system has a definable objective or function. There often is some sense in which the systems are engineered. We address this topic directly when we discuss and contrast self-organization and organization by design.

A central goal of this text is to develop models and modeling techniques that are useful when applied to all complex systems. For this we will adopt both analytic tools and computer simulation. Among the analytic techniques are statistical mechanics and stochastic dynamics. Among the computer simulation techniques are cellular automata and Monte Carlo. Since analytic treatments do not yield complete theories of complex systems, computer simulations play a key role in our understanding of how these systems work.

The human brain is an important example of a complex system formed out of its component neurons. Computers might similarly be understood as complex interacting systems of transistors. Our brains are well suited for understanding complex systems, but not for simulating them. Why are computers better suited to simulations of complex systems? One could point to the need for precision that is the traditional domain of the computer. However, a better reason would be the difficulty the brain has in keeping track of many and arbitrary interacting objects or events—we can typically remember seven independent pieces of information at once. The reasons for this are an important part of the design of the brain that make it powerful for other purposes. The architecture of the brain will be discussed beginning in Chapter 2.

The study of the dynamics of complex systems creates a host of new interdisciplinary fields. It not only breaks down barriers between physics, chemistry and biology, but also between these disciplines and the so-called soft sciences of psychology, sociology, economics, and anthropology. As this breakdown occurs it becomes necessary to introduce or adopt a new vocabulary. Included in this new vocabulary are words that have been considered taboo in one area while being extensively used in another. These must be adopted and adapted to make them part of the interdisciplinary discourse. One example is the word "mind." While the field of biology studies the brain, the field of psychology considers the mind. However, as the study of neural networks progresses, it is anticipated that the function of the neural network will become identified with the concept of mind.

Another area in which science has traditionally been mute is in the concept of meaning or purpose. The field of science traditionally has no concept of values or valuation. Its objective is to describe natural phenomena without assigning positive or negative connotation to the description. However, the description of complex systems requires a notion of purpose, since the systems are generally purposive. Within the context of purpose there may be a concept of value and valuation. If, as we will attempt to do, we address society or civilization as a complex system and identify its purpose, then value and valuation may also become a concept that attains scientific significance. There are even further possibilities of identifying value, since the very concept of complexity allows us to identify value with complexity through its difficulty of replacement. As is usual with any scientific advance, there are both dangers and opportunities with such developments.

Finally, it is curious that the origin and fate of the universe has become an accepted subject of scientific discourse—cosmology and the big bang theory—while the fate of humankind is generally the subject of religion and science fiction. There are exceptions to this rule, particularly surrounding the field of ecology—limits to population growth, global warming—however, this is only a limited selection of topics that could be addressed. Overcoming this limitation may be only a matter of having the appropriate tools. Developing the tools to address questions about the dynamics of human civilization is appropriate within the study of complex systems. It should also be recognized that as science expands to address these issues, science itself will change as it redefines and changes other fields.

Different fields are often distinguished more by the type of questions they ask than the systems they study. A significant effort has been made in this text to articulate questions, though not always to provide complete answers, since questions that define the field of complex systems will inspire more progress than answers at this early stage in the development of the field.

Like other fields, the field of complex systems has many aspects, and any text must make choices about which material to include. We have suggested that complex systems have more than a few parts and less than too many of them. There are two approaches to this intermediate regime. The first is to consider systems with more than a few parts, but still a denumerable number—denumerable, that is, by a single person in a reasonable amount of time. The second is to consider many parts, but just fewer than too many. In the first approach the main task is to describe the behavior of a particular system and its mechanism of operation—the function of a neural network of a few to a few hundred neurons, a few-celled organism, a small protein, a few people, etc. This is done by describing completely the role of each of the parts. In the second approach, the precise number of parts is not essential, and the main task is a statistical study of a collection of systems that differ from each other but share the same structure—an ensemble of systems. This approach treats general properties of proteins, neural networks, societies, etc. In this text, we adopt the second approach. However, an interesting twist to our discussion is that we will show that any complex system requires a description as a particular few-part system. A complementary volume to the present one would consider examples of systems with only a few parts and analyze their function with a view toward extracting general principles. These principles would complement the seemingly more general analysis of the statistical approach.

The order of presentation of the topics in this text is a matter of taste. Many of the chapters are self-contained discussions of a particular system or question. The first chapter contains material that provides a foundation for the rest. Part of the role of this chapter is the introduction of "simple" models upon which the remainder of the text is based. Another role is the review of concepts and techniques that will be used in later chapters so that the text is more self-contained. Because of the interdisciplinary nature of the subject matter, the first chapter is considered to have particular importance. Some of the material should be familiar to most graduate students, while other material is found only in the professional literature. For example, basic probability theory is reviewed, as well as the concepts and properties of cellular automata. The purpose is to enable this text to be read by students and researchers with a variety of backgrounds. However, it should be apparent that digesting the variety of concepts after only a brief presentation is a difficult task. Additional sources of material are listed at the end of this text.

Throughout the book, we have sought to limit advanced formal discussions to a minimum. When possible, we select models that can be described with a simpler formalism than must be used to treat the most general case possible. Where additional layers of formalism are particularly appropriate, reference is made to other literature. Simulations are described at a level of detail that, in most cases, should enable the student to perform and expand upon the simulations described. The graphical display of such simulations should be used as an integral part of exposure to the dynamics of these systems. Such displays are generally effective in developing an intuition about what are the important or relevant properties of these systems.

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Yaneer Bar-Yam
Newton, Massachusetts, June 1997