Chapter 1

Introduction

1.1 Complex Systems in a Nutshell

It may be rather unusual to begin a textbook with an outright definition of a topic, but anyway, here is what we mean by *complex systems* in this textbook[1]:

> Complex systems are networks made of a number of components that interact with each other, typically in a nonlinear fashion. Complex systems may arise and evolve through self-organization, such that they are neither completely regular nor completely random, permitting the development of emergent behavior at macroscopic scales.

These properties can be found in many real-world systems, e.g., gene regulatory networks within a cell, physiological systems of an organism, brains and other neural systems, food webs, the global climate, stock markets, the Internet, social media, national and international economies, and even human cultures and civilizations.

To better understand what complex systems are, it might help to know what they are *not*. One example of systems that are not complex is a collection of independent components, such as an ideal gas (as discussed in thermodynamics) and random coin tosses (as discussed in probability theory). This class of systems was called *"problems of disorganized complexity"* by American mathematician and systems scientist Warren Weaver [2]. Conventional statistics works perfectly when handling such independent entities. Another example, which is at the other extreme, is a collection of strongly coupled compo-

[1] In fact, the first sentence of this definition is just a bit wordier version of Herbert Simon's famous definition in his 1962 paper [1]: "[A] complex system [is a system] made up of a large number of parts that interact in a nonsimple way."

nents, such as rigid bodies (as discussed in classical mechanics) and fixed coin tosses (I'm not sure which discipline studies this). Weaver called this class of systems *"problems of simplicity"* [2]. In this class, the components of a system are tightly coupled to each other with only a few or no degrees of freedom left within the system, so one can describe the collection as a single entity with a small number of variables. There are very well-developed theories and tools available to handle either case. Unfortunately, however, most real-world systems are somewhere in between.

Complex systems science is a rapidly growing scientific research area that fills the huge gap between the two traditional views that consider systems made of either completely independent or completely coupled components. This is the gap where what Weaver called *"problems of organized complexity"* exist [2]. Complex systems science develops conceptual, mathematical, and computational tools to describe systems made of *interdependent* components. It studies the structural and dynamical properties of various systems to obtain general, cross-disciplinary implications and applications.

Complex systems science has multiple historical roots and topical clusters of concepts, as illustrated in Fig. 1.1. There are two core concepts that go across almost all subareas of complex systems: emergence and self-organization.

The idea of *emergence* was originally discussed in philosophy more than a century ago. There are many natural phenomena where some property of a system observed at macroscopic scales simply can't be reduced to microscopic physical rules that drive the system's behavior. For example, you can easily tell that a dog wagging its tail is alive, but it is extremely difficult to explain what kind of microscopic physical/chemical processes going on in its body are making this organism "alive." Another typical example is your consciousness. You know you are conscious, but it is hard to describe what kind of neurophysiological processes make you a "conscious" entity. Those macroscopic properties (livingness, consciousness) are called emergent properties of the systems.

Despite its long history of discussion and debate, there are still a number of different definitions for the concept of emergence in complex systems science. However, the one thing that is common in most of the proposed definitions is that the emergence is about the system's properties at different *scales*. If you observe a property at a macroscopic scale that is fundamentally different from what you would naturally expect from microscopic rules, then you are witnessing emergence. More concisely, emergence is a nontrivial relationship between the system's properties at different scales. This definition was proposed by complex systems scientist Yaneer Bar-Yam [4]. I will adopt this definition since it is simple and consistent with most of the definitions proposed in the literature.

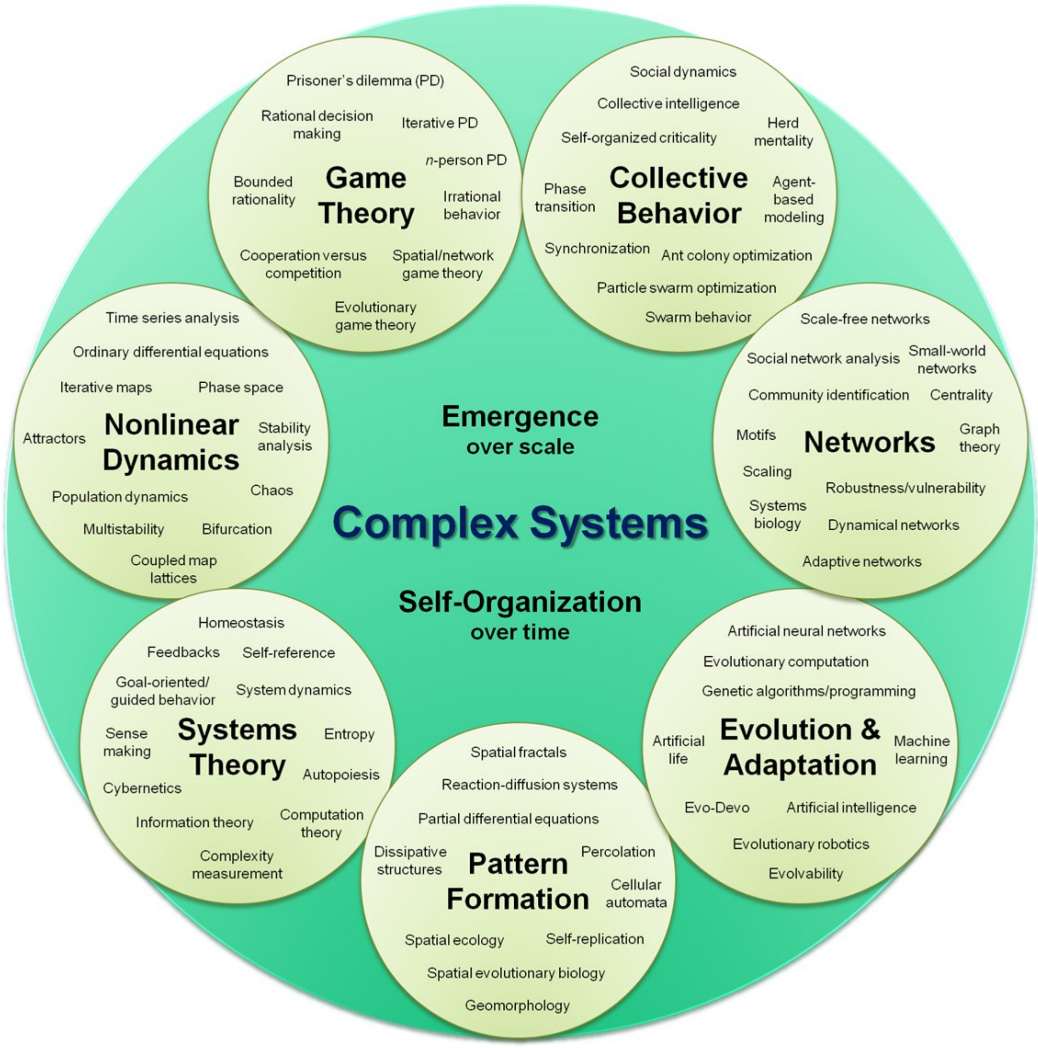

Figure 1.1: Visual, organizational map of complex systems science broken into seven topical areas. The three circles on the left (Nonlinear Dynamics, Systems Theory, and Game Theory) are the historical roots of complex systems science, while the other four circles (Pattern Formation, Evolution and Adaptation, Networks, and Collective Behavior) are the more recently studied topical areas. Created by the author and available from Wikipedia [3].

Emergence is a nontrivial relationship between the properties of a system at microscopic and macroscopic scales. Macroscopic properties are called *emergent* when it is hard to explain them simply from microscopic properties.

Another key idea of complex systems science is *self-organization*, which is sometimes confused with emergence. Some researchers even use these terms almost interchangeably. One clear distinction, though, is that, while emergence is about scale, self-organization is about time (in addition to scale). Namely, you call something *self-organizing* when you observe that the system spontaneously organizes itself to produce a nontrivial macroscopic structure and/or behavior (or "order," if you will) as time progresses. In other words, self-organization is a dynamical process that looks as if it were going against the second law of thermodynamics (which states that entropy of a closed system increases monotonically over time). Many physical, biological, and social systems show self-organizing behavior, which could appear mysterious when people were not aware of the possibility of self-organization. Of course, these systems are not truly going against the law of thermodynamics, because they are open systems that are driven by energy flow coming from and going to the outside of the system. In a sense, the idea of self-organization gives a dynamical explanation for emergent properties of complex systems.

Self-organization is a dynamical process by which a system spontaneously forms nontrivial macroscopic structures and/or behaviors over time.

Around these two key ideas, there are several topical clusters, which are illustrated in Fig. 1.1. Let's quickly review them.

1.2 Topical Clusters

Nonlinear dynamics is probably the topical cluster that has the longest history, at least from as far back as the 17th century when Isaac Newton and Gottfried Wilhelm Leibniz invented calculus and differential equations. But it was found only in the 20th century that systems that include nonlinearity in their dynamics could show some weird behaviors, such as *chaos* [5, 6] (which will be discussed later). Here, *nonlinearity* means that the outputs of a system are not given by a linear combination of the inputs. In the context of system behavior, the inputs and outputs can be the current and next states of the system, and if their relationship is not linear, the system is called a *nonlinear system*.

The possibility of chaotic behavior in such nonlinear systems implies that there will be no analytical solutions generally available for them. This constitutes one of the several origins of the idea of complexity.

Systems theory is another important root of complex systems science. It rapidly developed during and after World War II, when there was a huge demand for mathematical theories to formulate systems that could perform computation, control, and/or communication. This category includes several ground-breaking accomplishments in the last century, such as Alan Turing's foundational work on theoretical computer science [7], Norbert Wiener's cybernetics [8], and Claude Shannon's information and communication theories [9]. A common feature shared by those theories is that they all originated from some engineering discipline, where engineers were facing real-world complex problems and had to come up with tools to meet societal demands. Many innovative ideas of systems thinking were invented in this field, which still form the key components of today's complex systems science.

Game theory also has an interesting societal background. It is a mathematical theory, established by John von Neumann and Oskar Morgenstern [10], which formulates the decisions and behaviors of people playing games with each other. It was developed during the Cold War, when there was a need to seek a balance between the two mega powers that dominated the world at that time. The rationality of the game players was typically assumed in many game theory models, which made it possible to formulate the decision making process as a kind of deterministic dynamical system (in which either decisions themselves or their probabilities could be modeled deterministically). In this sense, game theory is linked to nonlinear dynamics. One of the many contributions game theory has made to science in general is that it demonstrated ways to model and analyze human behavior with great rigor, which has made huge influences on economics, political science, psychology, and other areas of social sciences, as well as contributing to ecology and evolutionary biology.

Later in the 20th century, it became clearly recognized that various innovative ideas and tools arising in those research areas were all developed to understand the behavior of systems made of multiple interactive components whose macroscopic behaviors were often hard to predict from the microscopic rules or laws that govern their dynamics. In the 1980s, those systems began to be the subject of widespread interdisciplinary discussions under the unified moniker of "complex systems." The research area of complex systems science is therefore inherently interdisciplinary, which has remained unchanged since the inception of the field. The recent developments of complex systems research may be roughly categorized into four topical clusters: pattern formation, evolution and adaptation, networks, and collective behavior.

Pattern formation is a self-organizing process that involves space as well as time. A system is made of a large number of components that are distributed over a spatial domain, and their interactions (typically local ones) create an interesting spatial pattern over time. *Cellular automata*, developed by John von Neumann and Stanisław Ulam in the 1940s [11], are a well-known example of mathematical models that address pattern formation. Another modeling framework is *partial differential equations* (PDEs) that describe spatial changes of functions in addition to their temporal changes. We will discuss these modeling frameworks later in this textbook.

Evolution and *adaptation* have been discussed in several different contexts. One context is obviously evolutionary biology, which can be traced back to Charles Darwin's evolutionary theory. But another, which is often discussed more closely to complex systems, is developed in the *"complex adaptive systems"* context, which involves *evolutionary computation*, *artificial neural networks*, and other frameworks of man-made adaptive systems that are inspired by biological and neurological processes. Called *soft computing*, *machine learning*, or *computational intelligence*, nowadays, these frameworks began their rapid development in the 1980s, at the same time when complex systems science was about to arise, and thus they were strongly coupled—conceptually as well as in the literature. In complex systems science, evolution and adaptation are often considered to be general mechanisms that can not only explain biological processes, but also create non-biological processes that have dynamic learning and creative abilities. This goes well beyond what a typical biological study covers.

Finally, *networks* and *collective behavior* are probably the most current research fronts of complex systems science (as of 2015). Each has a relatively long history of its own. In particular, the study of networks was long known as *graph theory* in mathematics, which was started by Leonhard Euler back in the 18th century. In the meantime, the recent boom of network and collective behavior research has been largely driven by the availability of increasingly large amounts of data. This is obviously caused by the explosion of the Internet and the WWW, and especially the rise of mobile phones and social media over the last decade. With these information technology infrastructures, researchers are now able to obtain high-resolution, high-throughput data about how people are connected to each other, how they are communicating with each other, how they are moving geographically, what they are interested in, what they buy, how they form opinions or preferences, how they respond to disastrous events, and the list goes on and on. This allows scientists to analyze the structure of networks at multiple scales and also to develop dynamical models of how the collectives behave. Similar data-driven movements are also seen in biology and medicine (e.g., behavioral ecology, systems biology, epidemiology), neuroscience (e.g., the Human Connectome Project [12]), and other areas. It is expected that these topical areas will expand further in the coming decades as the understanding of the collective dynamics of complex systems will increase their relevance in our everyday lives.

Here, I should note that these seven topical clusters are based on my own view of the field, and they are by no means well defined or well accepted by the community. There must be many other ways to categorize diverse complex systems related topics. These clusters are more or less categorized based on research communities and subject areas, while the methodologies of modeling and analysis traverse across many of those clusters. Therefore, the following chapters of this textbook are organized based on the methodologies of modeling and analysis, and they are not based on specific subjects to be modeled or analyzed. In this way, I hope you will be able to learn the "how-to" skills systematically in the most generalizable way, so that you can apply them to various subjects of your own interest.

Exercise 1.1 Choose a few concepts of your own interest from Fig. 1.1. Do a quick online literature search for those words, using Google Scholar (`http://scholar.google.com/`), arXiv (`http://arxiv.org/`), etc., to find out more about their meaning, when and how frequently they are used in the literature, and in what context.

Exercise 1.2 Conduct an online search to find visual examples or illustrations of some of the concepts shown in Fig. 1.1. Discuss which example(s) and/or illustration(s) are most effective in conveying the key idea of each concept. Then create a short presentation of complex systems science using the visual materials you selected.

Exercise 1.3 Think of other ways to organize the concepts shown in Fig. 1.1 (and any other relevant concepts you want to include). Then create your own version of a map of complex systems science.

Now we are ready to move on. Let's begin our journey of complex systems modeling and analysis.