Preface

> *REDUCTIONISM is the most natural thing in the world to grasp. It's simply the belief that "a whole can be understood completely if you understand its parts, and the nature of their 'sum'." No one in her left brain could reject reductionism.*
> —Douglas Hofstadter, *Gödel, Escher, Bach: an Eternal Golden Braid*

Reductionism has been the dominant approach to science since the 1600s. René Descartes, one of reductionism's earliest proponents, described his own scientific method thus: "to divide all the difficulties under examination into as many parts as possible, and as many as were required to solve them in the best way" and "to conduct my thoughts in a given order, beginning with the *simplest* and most easily understood objects, and gradually ascending, as it were step by step, to the knowledge of the most *complex*."[1]

Since the time of Descartes, Newton, and other founders of the modern scientific method until the beginning of the twentieth century, a chief goal of science has been a reductionist explanation of all phenomena in terms of fundamental physics. Many late nineteenth century scientists agreed with the well-known words of physicist Albert Michelson, who proclaimed in 1894 that "it seems probable that most of the grand underlying principles have been firmly established and that further advances are to be sought chiefly in the rigorous application of these principles to all phenomena which come under our notice."

Of course within the next thirty years, physics would be revolutionized by the discoveries of relativity and quantum mechanics. But twentieth century science was also marked by the demise of the reductionist dream. In spite of its great successes explaining the very large and very small, fundamental physics, and more generally, scientific reductionism, have been notably mute in explaining the complex phenomena closest to our human-scale concerns.

Many phenomena have stymied the reductionist program: the seemingly irreducible unpredictability of weather and climate; the intricacies and adaptive nature of living organisms and the diseases that threaten them; the economic, political, and cultural behavior of societies; the growth and effects of modern technology and communications networks; and the nature of intelligence and the prospect for creating it in computers. The antireductionist catch-phrase, "the whole is more than the sum of its parts," takes on increasing significance as new sciences such as chaos, systems biology, evolutionary economics, and network theory move beyond reductionism to explain how complex behavior can arise from large collections of simpler components.

By the mid-twentieth century, many scientists realized that such phenomena cannot be pigeonholed into any any single discipline but require an interdisciplinary understanding based on scientific foundations that have not yet been invented. Several attempts at building those foundations include (among others) the fields of cybernetics, synergetics, systems science, and, more recently, the science of "complex systems."

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[1] Full references for all quotations are given in the endnotes.

In 1984, a diverse interdisciplinary group of twenty-four prominent scientists and mathematicians met in the high desert of Santa Fe, New Mexico, to discuss these "emerging syntheses in science." Their goal was to plot out the founding of a new research institute that would "pursue research on a large number of highly complex and interactive systems which can be properly studied only in an interdisciplinary environment" and "promote a unity of knowledge and a recognition of shared responsibility that will stand in sharp contrast to the present growing polarization of intellectual cultures." Thus the Santa Fe Institute was created as a center for the study of complex systems.

In 1984 I had not yet heard the term complex systems, though these kinds of ideas were already in my head. I was a first-year graduate student in Computer Science at the University of Michigan, where I had come to study *artificial intelligence*; that is, how to make computers think like people. One of my motivations was, in fact, to understand how *people* think—how abstract reasoning, emotions, creativity, and even consciousness emerge from trillions of tiny brain cells and their electrical and chemical communications. Having been deeply enamored of physics and reductionist goals, I was going through my own antireductionist epiphany, realizing that not only did current-day physics have little, if anything, to say on the subject of intelligence but that even neuroscience, which actually focused on those brain cells, had very little understanding of how thinking arises from brain activity. It was becoming clear that the reductionist approach to cognition was misguided—we just couldn't understand it at the level of individual neurons, synapses, and the like.

Therefore, although I didn't yet know what to call it, the program of complex systems resonated strongly with me. I also felt that my own field of study, computer science, had something unique to offer. Influenced by the early pioneers of computation, I felt that *computation* as an idea goes much deeper than operating systems, programming languages, databases, and the like; the deep ideas of computation are intimately related to the deep ideas of life and intelligence. At Michigan I was lucky enough to be in a department in which "computation in natural systems" was as much a part of the core curriculum as software engineering or compiler design.

In 1989, at the beginning of my last year of graduate school, my Ph.D. advisor, Douglas Hofstadter, was invited to a conference in Los Alamos, New Mexico, on the subject of "emergent computation." He was too busy to attend, so he sent me instead. I was both thrilled and terrified to present work at such a high-profile meeting. It was at that meeting that I first encountered a large group of people obsessed with the same ideas that I had been pondering. I found that they not only had a name for this collection of ideas—complex systems—but that their institute in nearby Santa Fe was exactly the place I wanted to be. I was determined to find a way to get a job there.

Persistence, and being in the right place at the right time, eventually won me an invitation to visit the Santa Fe Institute for an entire summer. The summer stretched into a year, and that stretched into additional years. I eventually became one of the institute's resident faculty. People from many different countries and academic disciplines were there, all exploring different sides of the same question. How do we move beyond the traditional paradigm of reductionism toward a new understanding of seemingly irreducibly complex systems?

The idea for this book came about when I was invited to give the Ulam Memorial Lectures in Santa Fe—an annual set of lectures on complex systems for a general audience, given in honor of the great mathematician Stanislaw Ulam. The title of my lecture series was "The Past and Future of the Sciences of Complexity." It was very challenging to figure out how to introduce the audience of nonspecialists to the vast territory of complexity, to give them a feel for what is already known and for the daunting amount that remains to be learned. My role was like that of a tour guide in a large, culturally rich foreign country. Our schedule permitted only a short time to hear about the historical background, to visit some important sites, and to get a feel for the landscape and culture of the place, with translations provided from the native language when necessary.

This book is meant to be a much expanded version of those lectures—indeed, a written version of such a tour. It is about the questions that fascinate me and others in the complex systems community, past and present: How is it that those systems in nature we call *complex* and *adaptive*—brains, insect colonies, the immune system, cells, the global economy, biological evolution—produce such complex and adaptive behavior from underlying, simple rules? How can interdependent yet self-interested organisms come together to cooperate on solving problems that affect their survival as a whole? And are there any general principles or laws that apply to such phenomena? Can life, intelligence, and adaptation be seen as mechanistic and computational? If so, can we build truly intelligent and *living* machines? And if we can, would we want to?

I have learned that as the lines between disciplines begin to blur, the content of scientific discourse also gets fuzzier. People in the field of complex systems talk about many vague and imprecise notions such as spontaneous order, self-organization, and emergence (as well as complexity itself). A central purpose of this book is to provide a clearer picture of what these people are talking about and to ask whether such interdisciplinary notions and methods are likely to lead to useful science and to new ideas for addressing the most difficult problems faced by humans, such as the spread of disease, the unequal distribution of the world's natural and economic resources, the proliferation of weapons and conflicts, and the effects of our society on the environment and climate.

The chapters that follow give a guided tour, flavored with my own perspectives, of some of the core ideas of the sciences of complexity—where they came from and where they are going. As in any nascent, expanding, and vital area of science, people's opinions will differ (to put it mildly) about what the core ideas are, what their significance is, and what they will lead to. Thus my perspective may differ from that of my colleagues. An important part of this book will be spelling out some of those differences, and I'll do my best to provide glimpses of areas in which we are all in the dark or just beginning to see some light. These are the things that make science of this kind so stimulating, fun, and worthwhile both to practice and to read about. Above all else, I hope to communicate the deep enchantment of the ideas and debates and the incomparable excitement of pursuing them.

This book has five parts. In Part I I give some background on the history and content of four subject areas that are fundamental to the study of complex systems: information, computation, dynamics and chaos, and evolution. Parts II–IV describe how these four areas are being woven together in the science of complexity. I describe how life and evolution can be mimicked in computers, and conversely how the notion of *computation* itself is being imported to explain the behavior of natural systems. I explore the new science of networks and how it is discovering deep commonalities among systems as disparate as social communities, the Internet, epidemics, and metabolic systems in organisms. I describe several examples of how complexity can be measured in nature, how it is changing our view of living systems, and how this new view might inform the design of intelligent machines. I look at prospects of computer modeling of complex systems, as well as the perils of such models. Finally, in the last part I take on the larger question of the search for general principles in the sciences of complexity.

No background in math or science is needed to grasp what follows, though I will guide you gently and carefully through explorations in both. I hope to offer value to scientists and nonscientists alike. Although the discussion is not technical, I have tried in all cases to make it substantial. The endnotes give references to quotations, additional information on the discussion, and pointers to the scientific literature for those who want even more in-depth reading.

Have you been curious about the sciences of complexity? Would you like to come on such a guided tour? Let's begin.