

COMPLEX SYSTEMS

Boldly Going Beyond Mathematics

Christoph Adami

Before the computer age, progress in science was achieved mainly by the interaction of two processes: gathering empirical data and crafting theoretical descriptions of the forces and agents that give rise to our observations. The story of how theories—perhaps inspired by new observations—make falsifiable predictions that are then compared to further observations and, possibly, refinements of the theory has been told many times. This theory-observation-refinement cycle has arguably provided many of our most profound insights into how the universe works, in particular in physics and chemistry. It has not worked so well for developing our understanding of complex systems.

For one thing, complex systems do not easily lend themselves to analysis, the process of taking apart a system and examining its components individually. If taken apart, many complex systems lose precisely the character that makes them complex. The essence of these systems, then, seems to lie not in the nature of their components but in how the components interact—across different hierarchies, in synergistic and antagonistic manners. The agents within these systems are heterogeneous (think participants in a market economy or molecules within a cell), and their behavior is influenced by the type and quantity of other agents nearby. Such systems defy description with the traditional tool of theory builders: mathematics. Instead, they must be modeled by taking into account the rules of interaction, the natures of the agents, and the way the

agents, rules, and ultimately whole systems came about. In his *Signals and Boundaries: Building Blocks for Complex Adaptive Systems*, John Holland proposes that computational modeling is the appropriate tool not only for describing but, fundamentally, for understanding such systems. In particular, he argues that this modeling approach is in no way inferior to a mathematical one. Rather, he advocates that the computational modeling of signal-boundary systems (which I will describe in more detail below) goes where mathematics cannot go while being no less rigorous, no less exact.

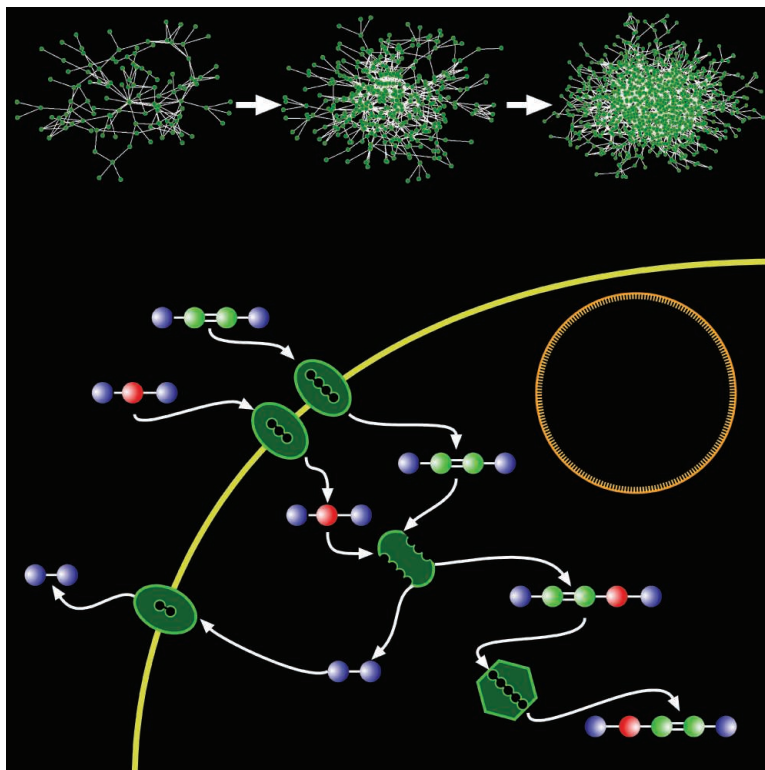
Now 83, Holland, a computer scientist and psychologist at the University of Michigan, has thought about complex systems for a long time. One of the fathers of the field of evolutionary computation, he is widely credited for having invented a machine-learning method based on the genetic pro-

cesses of inheritance, mutation, recombination, and selection: the genetic algorithm. He has also written extensively about cognitive science, the brain as a complex system, and adaptation in general (1). Indeed, perhaps the most outstanding aspect of the computational approach that he describes is that it must be evolutionary: the signals and the boundaries that are the system must be the result of a coevolutionary process.

But let me step back and describe what Holland means when discussing signal-boundary systems. In any complex system, agents make decisions that affect not only their own fate but also the actions and decisions of other agents—and the very system within which these decisions are made. The reach of these actions is not infinite, and the source of the information that was used to generate them cannot be infinitely remote. The dynamics of the system are influenced by both the signals and the boundaries within which the signals originate or are received. In a cell, for example, there are myriad agents (proteins) that process signals (small molecules and other proteins), and they interact with cellular or organelle boundaries. In a society, the agents are a diverse set of people with different roles, and the signals through which they interact depend on (and are shaped by) the boundaries (of home, city, or country). Naturally, boundaries are not impermeable, nor are they permanent. The book focuses on understanding how these boundaries transmit signals and how boundaries within boundaries give rise to hierarchically organized systems.

Because the formalism for the description of signal-boundary systems should, in Holland's view, be applicable to any complex system (whether a cell, an organism, a company, or a country), it is necessarily abstract. Indeed, it is an amalgamation of a number of toolboxes that have been developed over time, including classifier systems, genetic algorithms, urn models, and several others. Holland calls such amalgams “dynamic generated systems,” because the ultimate rules agents use to process signals are dynamically

Signals and Boundaries
Building Blocks for
Complex Adaptive Systems
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An example. Signals and boundaries in the artificial cell model (3) and the metabolic networks that evolve in them.

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generated within the system. They are not designed. Nor are the boundaries designed: they should emerge in the coevolutionary process that selects for agents that make appropriate decisions given the environment within which they operate.

This may sound like a radical approach to modeling, in particular because Holland emphasizes that these models do not, strictly speaking, model anything. Rather, they are exploratory in nature: They are aimed at exploring the consequences of the underlying model assumptions. If the predictions (after evolving the model through thousands if not millions of generations) contradict our observations, we have to go back and question the model assumptions. In this way, computational modeling plays exactly the role that theory has played, only packed with the power of computers that mathematics alone cannot achieve.

But the approach is less radical than one might think. Such approaches have been quite successful in the past. For example, the Avida system that was designed to study basic evolutionary dynamics (2) can be seen broadly as an instantiation of such a signal-boundary system, complete with a symbolic basis, grammar, niches, ecologies, signal processing, and, of course, evolution. And Avida is exploratory in the sense that it has generated hypotheses about the natural world that subsequently have been tested there. Another candidate signal-boundary system is the artificial cell model (3). In it, nearly every one of Holland's requirements for such a system has been implemented, and it too can be used to make falsifiable predictions about the natural world even though the model itself is artificial, an abstraction.

Signals and Boundaries hearkens back to another influential book within the field of complexity research, Herbert Simon's *The Sciences of the Artificial* (4), which in its third (1996) edition received a new chapter dealing with the genetic algorithms and adaptive systems championed by Holland. But Holland's book is different in an important aspect. It becomes technical when mathematics is needed, and Holland does not shy away from introducing complicated computational structures. In these passages (and chapters), it becomes less of a science book for the interested lay person (as Simon's book is) and more of a textbook. In this respect it bears some resemblance to Douglas Hofstadter's *Gödel, Escher, Bach* (5), which (in the field of cognitive science) also did not shy away from being both technical and ambitious. However, Holland's book is much more succinct, clocking in at 301 duo-

decimo pages, compared with the 777 quarto pages of Hofstadter's classic.

Signals and Boundaries is indeed an ambitious book because Holland advocates (correctly in my mind) a culture that does not treat computational approaches as "mere models," as if they were inferior or less rigorous than purely mathematical treatments. Perhaps it would have been strengthened had the author drawn more from existing modeling endeavors that have followed his vision almost to the t. But it is still a "remarkable achievement" (as Holland's colleague Robert Axelrod calls it on the dust jacket)—not the least because it would qualify as such had it been written by someone much younger.

References

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COMPUTER SCIENCE

Casting a Wider Net

Lynn Andrea Stein

Mung Chiang's *Networked Life: 20 Questions and Answers* has an intriguing premise and an ambitious vision. As the book's title suggests, Chiang sets out to explain the various technologies that underpin all facets of our interconnected society. His approach begins with the questions of the subtitle—20 curiosities of how (and why) it is that our networked world works. He goes on to provide multilayered answers intended in turn for the interested public, for undergraduates, and for a sophisticated advanced readership. To further up the ante, the book is also the text associated with a massive open online course (MOOC)—*Networks: Friends, Money, and Bytes* (1)—offered for free

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through Coursera (with videos also on YouTube) alongside its more conventional incarnation at Princeton University.

Chiang intends for the book to provide something for everyone. Its topic matter ranges from Netflix's movie recommendations to Verizon's pricing model, from building a Twitter following to Skyping for free. *Networked Life* explores phenomena that may seem obscure to the general public—such as cloud computing, TCP/IP (Transmission Control Protocol/Internet Protocol), and CDMA (Code-Division Multiple Access) cell phone infrastructure—as well as pop culture memes like "going viral" and the old chestnut about six degrees of separation. The topics are broad ranging and the influences equally eclectic. Each of the 20 questions is meant to draw in readers by addressing some familiar phenomenon, pulling aside the curtains to show how the technology really works.

The book has its roots in an innovative course taught by Chiang to undergraduate electrical and computer engineers at Princeton University. Bridging disciplinary boundaries, introducing mathematics only as needed, and drawing connections across disparate phenomena using graph, optimization, game, and learning theory, this unusual course teaches in an integrated and application-specific way. Chiang's framing of the material as 20 intriguing questions about networks, their architectures, and associated phenomena ties theory to practical systems that students encounter every day. The shift from comprehensive content coverage to thematically organized material with real-world applications is a step toward the future of learning. Just in time trumps just in case in a world where knowledge is increasingly available, where which and why and how become more critical than what. Chiang's course

surely pushes the boundaries of the traditional lecture, and the book similarly is meant to be a next-generation work.

Chiang would like it to serve as both an undergraduate textbook and a broadly accessible popular work. The opening part of each chapter offers "a short answer"

devoid of mathematics, up to nine pages, meant to give the novice a sense of how the rest of the explanation will proceed. Chiang expands on this in "a longer answer" (sometimes occupying fewer pages) suitable for "primarily juniors and seniors in electrical engineering and computer science" or others with similar background including "differen-

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