To Complexity and Beyond! Review of *Complexity: A Guided Tour*

Reviewed by Dan Rockmore

Complexity: A Guided Tour
Melanie Mitchell
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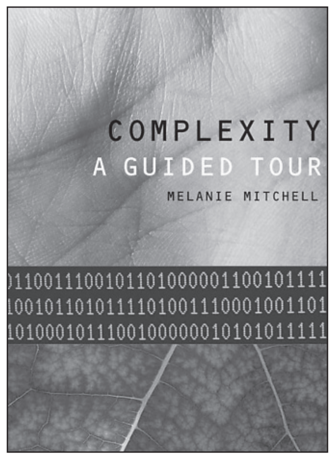
If the interests of the funding agencies provide any sort of measuring stick for the coming of age of a discipline, then it would seem that the study of "complex systems" has recently become must-see science. You would be hard pressed to find in any collection of recent requests for proposals an organization that is not looking to explicitly leverage the framework of complex systems, to engender a deeper understanding of its basic interests, be they health, defense, communications, ecology, economics, markets, society, and even culture.

That these phenomena all might admit a unified methodological approach suggests that they share some basic characteristics. One of the first people to see these disciplinary trees as a forest was the polymath Herbert Simon (1916–2001). Simon worked at the highest levels in the economic, social, and computer sciences. He was a founder of artificial intelligence, winner of the Turing Award and of the Nobel Prize in Economics, and a leading figure in modern psychology.

In his eloquent "The Organization of Complex Systems" [1] (the paper that named the field), Simon points out that what these and other phenomena have in common is a "Darwinian nature", that is to say, an evolutionary character given by a partially ordered hierarchical structure whose components interact on widely varying time scales and in whose development we see selection, adaptation, mutation, hysteresis, and contingency. Perhaps most notably, we find a good deal of "nonlinearity", not only in particular measurable qualities at specific time scales but also across scales as we attempt to relate the structures (and understandings) from one scale to the next, only to find that they do not scale themselves, a phenomenon often referred to as "emergence". The standard straw man of comparison here is particle physics. There, presumably, the basic behavior of matter is well explained by molecular understandings, which in turn is supported by atomic studies, and so on; one turtle happily perched upon the next. In comparison, understandings of neuron-to-neuron activity via the Hodgkin-Huxley equations does not (yet?) lead us step-by-step (or turtle-by-turtle) to any understanding of mind; a simple formulation of the interactions between one buyer and one seller does not allow us to predict the dynamics of the New York Stock Exchange. Nevertheless, in each of these (and other) instances, structure does exist at the macro and micro levels, as well as many levels in between. How? Why? In Simon's view the explanation is partly that evolved systems are generally only "weakly decomposable" and that a main goal of studying such a diversity of (complex) systems is the "formulation of laws that express the invariant relations between successive levels in the hierarchy" which ultimately require a "Mendelian" explanation.



It would be something of an overstatement to suggest that the single paper by Simon launched a thousand others, but in the time between then and now a field of "complex systems" has indeed emerged, realizing the idea that the general mechanisms

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of evolution as expressed in a wide range of phenomena could be profitably addressed in a rigorous and coherent way, as an inherently a-disciplinary (in the sense of classical disciplinary categorizations) activity.

Mitch Waldrop's *Complexity: The Emerging Science at the Edge of Order and Chaos* [2] was the book that put complex systems on the map. Waldrop tells his story through the tale of the birth of the Santa Fe Institute, arguably the preeminent research center of complex systems studies in the world, but in 1984 little more than a somewhat inchoate thought shared among several senior scientists at Los Alamos National Laboratory. All of these researchers were unhappy with LANL's trend toward compartmentalized and specialized science and thus both implicitly and explicitly concerned that the understandings of the micro were not getting at the big questions and problems of the day. Waldrop gives us a good sense of the emergence of the subject and the creation of SFI as something of a manifestation of a scientific and technological zeitgeist. We learn of an initial small meeting between economists and physicists (motivated by *that* era's financial crisis), Brian Arthur and the discovery of the paradoxical "increasing returns" and the El Farol problem, John Holland's invention of evolutionary computing and the early excitement about algorithmic and computational approaches to learning. Stuart Kauffman's invention of the N-K network, the first model of a genetic circuit, also plays a starring role, as do game theory and Robert Axelrod's "tournament" for playing iterated Prisoner's Dilemma that revealed the optimality of the "Tit-for-Tat" strategy (proposed by Anatol Rapoport). We see how the new research freedom (and excitement) afforded by increased access to computing, in part enabled by the beginnings of personal computing, catalyzed the work, helping to make possible early investigations of artificial life and cellular automata. Waldrop's book is a true and good popular science read, and it is fair to say that it helped to create much of the early interest in complex systems (along with Roger Lewin's nearly simultaneous *Complexity: Life at the Edge of Chaos* [3]).

Some twenty years later, the time is ripe to pay another visit to this place and see what kinds of modernizations have been effected. To this end, our view of complex systems science gets a long-awaited updating and deepening in Melanie Mitchell's *Complexity: A Guided Tour*. Mitchell is a complex systems insider, well known and respected in the complexity research community with particular expertise in the study of artificial intelligence, cellular automata, and evolutionary computing. Mitchell was a student of Douglas Hofstadter at the University of Michigan, where she learned genetic algorithms from John Holland. She then moved to the Santa Fe Institute, where she was a faculty member for several years, then up the road to Los Alamos and back to SFI. She is now professor of computer science at Portland State University. Mitchell remains a member of SFI's (geographically distributed) external faculty (as am I), and we are also colleagues on SFI's Science Steering Committee. She knows many of the big players in the field, both past and present, and the tone of the book is a friendly and personal one. This gives the book something of a Zelig-like feel to it, but appropriate to one who has been working in the field from a time close to its recent origins.

The sheer range of phenomena that fall under the complex systems heading, each with its own jargon and important details, might give pause to even the most seasoned expositor. Mitchell's well-written book (already a winner of the 2010 Phi Beta Kappa Science Book Award and on the long list for the Royal Society's 2010 book prize) meets the challenge by entwining concepts and topical "case studies" through a five-part structure and taking pains to connect the dots as often as is possible. Of the former, we find expositions of what I would call the "old" complex systems (such as some of those mentioned above) as well as the new. Of the old, the treatments here are generally pithier and clearer—a nice example of a genetic algorithm for search is perhaps the best I've ever read. The chestnuts of complexity are augmented by useful overviews of more recent work. I enjoyed the updating of cellular automata by a good explanation of the "particle" approach to studying CAs. The new science of networks is given significant room, making up the theme of the penultimate section. In this chapter and others in the book, much is made—and rightfully so—of the way in which massive data sets of all sorts of phenomena have truly been a game-changer in complexity analysis. Network theory was graph theory before we had in hand large real-world networks to explore. Scaling is addressed, both in and of itself, as well as in the context of the recent work of Geoffrey West, Jim Brown, and Brian Enquist (and others) on the mechanistic explanations for allometric scaling in terms of space-filling resource delivery systems. In these discussions as well as others, I appreciated the even-handedness with which Mitchell presented controversial work. She brings the scientific debate out for display, and the reader gets the sense of being drawn into the conversation and unconsciously or consciously spurred to engage with the results and the science. In places such as these I felt less like a receiver of information (as I did in the lengthy discussions of genetics) than a participant in a conversation and was all the more interested in it for that experience.

The "conceptual" parts are a welcome addition and, to my taste, perhaps the most interesting aspect of the book. Information and information processing, as well as computation, provide grand themes in the book (and are clearly Mitchell's strong suit), as does evolution. A discourse on the various definitions of "complexity" and the difficulties of finding a good definition that seems to work for living phenomena was fun. The art of modeling and the power (and potential pitfalls) also receive their due. The threading of these grand ideas through the topical studies gives one a good sense of the connectivity of the various phenomena and thus the sense that there is a subject here to be studied. It also helps bring out the inherent interdisciplinarity of the subject. A closing chapter on "The Past and Future of the Sciences of Complexity" gives a nice historical contextualization of all that has preceded it and also considers some of the objections raised by those who don't see complex systems as a subject.

In Mitchell's own words, the book is intended for "everyone", scientist and interested general reader alike, and in this she has presented herself with a significant challenge. Given such a goal, a certain amount of unevenness is to be expected, with the hills, plains, and valleys defined in the eyes and minds of the beholders. For this particular beholder, mathematician by training, and one who has become increasingly more applied than pure and developed an interest in complex systems, I couldn't keep myself from wishing that even more of the "new" might be found in this book. We particularly note Mitchell's clarity of exposition: that Prisoner's Dilemma and Tit-for-Tat would quickly bring us to the exciting new work in algorithmic [4] or evolutionary game theory [5] or policing and conflict [6] and more discussion of the extraordinary new possibilities for social science enabled by the Internet [7]; that the story of Lorenz's discovery of chaos might bring us to more recent work in collective dynamics related to both flocking and neuroscience [8] instead of artificial life and CAs (indeed, there is a relatively heavy emphasis on aspects of "evolutionary computing"), which has had a multitude of exposition; that we might now find some space for the very exciting new work being done on understanding a general notion of metabolism and its implications for new theories of the origin of life [9]. It was also somewhat surprising to find almost no discussion of econophysics, but some might say that in this market, that is a selling point….

Another part of this longing to see the new in this well-written book is my own personal hope that more of the mathematics community might become engaged in thinking about complex systems. Historically, the subject—even before it was a subject—has been fertile ground for mathematicians, and that is still true. Of course, deep connections already exist to the world of nonlinear dynamics, in both pure and applied contexts. To extend results from smooth dynamics to the strange topologies of real life networks—or at least large classes of them—is of great importance as people wrestle to understand dynamics on networks. Progress here also has the potential to add some significant understanding to the agent-based models that are often used to simulate complicated phenomena. In this direction, rigorous results in cellular automata are still of interest, while a great challenge is the creation of models that produce the multiple timescales of dynamics recognized by Simon decades ago. The oft-mentioned data explosion that has truly changed the field remains fertile ground for the development of more powerful statistical methods to understand the "patterns of activity" in complex phenomena. To this end, for example, one can point to the new field of computational topology, a natural (mutated!) descendant of algebraic topology, itself born of the study of that ever-intriguing complex system, the solar system. Turing's interest in the abstraction of computation generally, in the inanimate and animate, gave birth to automata theory, but more recently, the lambda calculus has been proposed as a more natural framework for understanding the "logic" of the cell [10]. Perhaps the notion of information and its processing as instantiated across living systems (e.g., cells, ecologies, societies, markets) requires a different kind of understanding or abstraction. Indeed, in her concluding and thought-provoking chapter on the past and future of complex systems studies, Mitchell suggests that a whole new mathematics might be necessary to perform the sought-after syntheses of complex systems studies.

That said, these are in some sense quibbles, and there is assuredly something in this book for everyone. With its generally clear writing and fine bibliography, for the uninitiated, Melanie Mitchell's *Complexity* is a great way to take a first voyage to the complex system of complex systems. We learn of its history, visit some of the modern hotspots, and, even more, are given a sense of the connections between these different times and places and are invited to speculate about how it will all look in a few years. It left me, and will surely leave any open-minded traveler, eager to continue to learn about this relatively unexplored and fertile world. Ultimately, that's precisely the hallmark of an excellent tour guide.

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