BOOKS: DOING SCIENCE

Is the Universe a Universal Computer?

Melanie Mitchell

History has seen the development of many new sciences but very few new kinds of science. New kinds of science involve radical changes in thinking, such as the shift from Aristotelian traditions to experimental methods and the description of natural phenomena in mathematical terms—revolutions associated with names like Galileo and Newton. Thus it is with no small risk of hubris that Stephen Wolfram titles his account of his approach to explaining the natural world *A New Kind of Science*. At over 1200 pages, his book rivals the combined lengths of Galileo's *Dialogues* and Newton's *Principia*. But does it fulfill the promise of its title and heft? Not very well.

A New Kind of Science
by Stephen Wolfram
Wolfram Media, Champaign, IL, 2002. 1280 pp. \$44.95, £40, C\$69.95. ISBN 1-57955-008-8.

The book's central idea is that the simple computer programs, namely cellular automata, can explain natural phenomena that have so far eluded "traditional" mathematical approaches such as differential equations. A cellular automaton, in its simplest incarnation, is a one-dimensional line of sites or cells, each of which is either black or white. The color (state) of the cell can change over time. At each discrete time step, every cell updates its state—either retaining or flipping its color from the previous step—as a function of its previous state and those of its two nearest neighbors. The cellular automaton rule comprises the list of functions that map each three-cell neighborhood to the update state for the center cell. In his theoretical work, Wolfram typically considers the lines of cells limitless to ensure there is no ambiguity at the boundaries. Such one-dimensional, two-state, two-neighbor cellular automata are called elementary; more complicated versions can have additional states per cell, larger neighborhoods to determine update states, and additional dimensions.

Cellular automata are perhaps the most idealized models of complex systems: they consist of large numbers of simple components (here, cells) with no central controller and limited communication among components. Originally defined and studied by the mathematicians Stanislaw Ulam and John von Neumann, cellular automata have been used as models for such natural phenomena as earthquakes, turbulent flow, biological pigmentation, and tumor growth. They have also been applied in computer science as idealizations of massively parallel, non-centralized computation.

Wolfram grounds his approach on six principal claims: Simple programs (i.e., elementary cellular automata) can produce highly complex and random-looking behavior. Such programs, implemented in natural systems, give rise to most of the complexity and randomness that we observe in nature. These programs lead to better models of complex systems than do traditional mathematical approaches. Computation in cellular automata and similar simple programs provide a new framework for understanding complex systems. Elementary cellular automata can exhibit the ability to perform any computable procedure. This computational universality gives rise to the principle of "computational equivalence," which Wolfram claims is a new law of nature that illuminates many aspects of natural phenomena as well as fundamental philosophical questions. Each of these ideas warrants careful consideration.

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Width doublers. These examples of three-color cellular automata that achieve the purpose of doubling the width of their initial condition were taken from the 4277 cases found in an exhaustive search of all of the more than 7.625 x 10^{12} possible rules.

Complexity from Simple Programs

Throughout the book, Wolfram presents many beautiful, striking pictures of the behavior of various cellular automata. These demonstrate that even elementary cellular automata can produce patterns ranging from simple to quite complicated, highly ordered to seemingly random. The great diversity of these patterns and the fact that such simple rules can produce such apparently complex behavior is viewed by Wolfram as deeply significant.

That simple rules can produce complex behavior is a very important idea, and it underlies the science of complex systems. However, Wolfram implies that the notion was his discovery and the field of complex systems his invention—an absurd claim. The idea of simple rules leading to complex behavior underlies much of dynamical systems theory and particularly the subset often known as "chaos theory." I don't know when the idea was first articulated, but by the early 1970s Nicholas Metropolis, Paul Stein, and Myron Stein (*1*) had provided a detailed explanation of the complex behavior of simple iterated maps (such as the famous "logistic map"). In the late 1960s, John Conway developed his "Game of Life," a simple two-dimensional cellular automaton capable of highly complex behavior (*2*). Around the same time, Aristid Lindenmayer invented what are now called L-systems, simple rules that give rise to extremely lifelike pictures of plants and other natural forms (*3*). One of Wolfram's own early contributions was observing and classifying such complex behavior in elementary cellular automata.

Origins of Complexity in Nature

In Wolfram's view, cellular automata or similar simple rules are responsible for most of the randomness and complexity seen in nature. To support this claim, he notes that randomness and complexity are very common in the behavior of simple rules and that some complex and random-looking phenomena in nature have visual features similar to those

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produced by simple cellular automata. He offers an important and useful discussion of the terms "random" and "complex." The meaning of both terms depends on the features of behavior that are of interest and the available perceptual and analytical tools. Wolfram examines these connections in considerable detail, and he devotes an entire chapter to a discussion of perception and analysis. Nonetheless, there is little support for his claim that because simple rules commonly produce random and complex-looking behavior, simple rules must be the source of most such behavior in nature.

In addition, Wolfram distances his results on cellular automata from earlier results on chaotic systems. He contends that whereas some cellular automata can generate randomness "intrinsically" (starting from a very simple initial condition), a chaotic system can do so only when its initial condition is random. This is incorrect; there are many chaotic systems in which even a very simple initial condition produces a random-looking output—the Lorenz system of equations (*4*) is one well-known example. In general, cellular automata are a type of discrete dynamical system and can exhibit behavior analogous to chaos. Thus, many of the results from the theory of dynamical systems apply to cellular automata.

Cellular Automata as Models

The author traces the origins of his new kind of science to his frustration with analytical approaches. He claims that, in contrast to traditional mathematics, the research program he develops in the book "is for the first time able to make meaningful statements about even immensely complex behavior." This promise is not borne out.

One chapter of the book presents patterns formed by cellular automata and similar systems that model crystal growth (particularly snowflakes), material fracture, fluid turbulence, plant morphologies, and pigmentation patterns of shells and animals. In each case, the behavior of the model visually resembles in some way the behavior of the actual system; this is particularly striking for snowflakes and sea shells. Wolfram makes a compelling visual case that simple cellular automata–like rules might underlie such behavior in nature, and he gives a concise and readable review of some ideas in developmental morphology. But the results in this chapter do not advance beyond work done twenty or more years ago, and there are no new "meaningful statements" about any of these phenomena.

Less compelling are Wolfram's speculations on natural selection. He contends that because the generation of complexity is so common in simple cellular automata, it must be common in nature as well and, therefore, natural selection is not needed to create complexity in biology. In his view, biological systems are complex merely because evolution has sampled a huge number of simple programs and these often give rise to complex behavior. Wolfram offers no convincing evidence for this claim, nor does he discuss where these programs are implemented—at the level of the genome? of cells? Although cellular automata provide plausible models of biological pigmentation and some aspects of morphology, there is as yet no compelling link between simple programs and complex biological systems such as the brain, the immune system, or cellular metabolism. On the contrary, it is increasingly clear that notions of selection and adaptation are crucial for understanding such systems.

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Pigmentation patterns on mollusc shells. Wolfram interprets their striking resemblance to the patterns produced by simple one-dimensional cellular automata as evidence that they are generated by processes whose basic rules are chosen at random from a set of the simplest possibilities.

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Framework for Understanding Nature

Since the beginning of the computer age, the process of computation has been proposed as an explanatory framework for many natural systems. Artificial-intelligence practitioners have suggested that the brain is actually a computer and that thinking is equivalent to processing information. In the earliest use of cellular automata, von Neumann described biological self-reproduction in computational terms (*5*, *6*). More recently, all kinds of behavior (including the immune response, the regulatory networks formed among genes, and the collective behavior of ants in a colony) have been cast as "natural computation." Wolfram takes this notion of "computation as a framework for nature" to an extreme. He believes that nearly everything in the universe can be explained not just as computation but specifically in terms of simple programs such as cellular automata. In a long, rather technical chapter, he discusses how fundamental physics (thermodynamics, quantum mechanics, relativity, and the like) can be cast in terms of cellular automata, a research program that was previously pursued by Edward Fredkin, Tomasso Toffoli, Norman Margolus, Konrad Zuse, and others [see (*7*)]. Wolfram claims that "remarkably simple programs are often able to capture the essence of what is going on—even though traditional efforts have been quite unsuccessful." But as far as I can tell, his approach has yielded no new successful predictions, and none of his interesting speculations on physics propose any experiments to support this view.

Computational Universality

A centerpiece of the book is Wolfram's sketch of a proof done by Caltech graduate student (and former Wolfram research assistant) Matthew Cook that one of the elementary cellular automaton rules can support universal computation. In describing this result, Wolfram gives an excellent review of some central ideas in theoretical computer science. The notion of universal computation was first developed by Alan Turing in the 1930s. Roughly, a device is said to be "universal" or "can support universal computation" if it can run any program on any input. Nowadays, approximations to a universal devices are commonplace; they are known as programmable computers. The computer on your desk can (given enough memory) calculate any function, as long as the function is "computable." (One of Turing's greatest contributions was to demonstrate that noncomputable functions exist.)

In the early 1980s, Wolfram had found that of the 256 possible elementary cellular automaton rules (i.e., rules for one-dimensional cellular automata with two states and two neighbors per cell), a small subset, including the rule he numbered 110, exhibited particularly interesting behavior. Cook showed that, for any program and any input, one can specially design an initial condition that encodes the program and input and then iterate rule 110 (of the 256 possible rules for a one-dimensional cellular automaton with two states and two neighbors per cell) on the initial condition to, in effect, run the given program on the given input. Thus, rule 110 is a universal computer. This is an impressive result, and Wolfram claims it is counterintuitive:

> [I]t has almost always been assumed… that in order to get something as sophisticated as universality there must be no choice but to set up rules that are themselves special and sophisticated. One of the dramatic discoveries of this book, however, is that this is not the case.

Wolfram views this accomplishment as extremely significant for science; he believes that a logical consequence is that universality is ubiquitous throughout nature. Rule 110's universality will not, however, be very surprising to computer scientists; Cook's proof is only the latest in a series of demonstrations that relatively simple devices (Turing machines, neural networks, iterative maps) can be universal computers. Von Neumann was the first to show that a cellular automaton can be universal. He constructed a two-dimensional example with 29 states and four neighbors per cell, and others eventually reduced the complexity to four states per cell (*8*). In the 1970s, Conway sketched a proof that his Game of Life (with two states and eight neighbors per cell) is universal (*2*). Before Cook's work with rule 110, the simplest known universal cellular automaton was one-dimensional with seven states and two neighbors per cell (*9*). Rule 110 is now the simplest, and it is hard to see how a universal cellular automaton could get any simpler. Although it is interesting that such a simple rule (not specifically constructed to perform computation) turns out to be universal, the result is an incremental step over what had been done before.

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A universal computer. Rule 110 uses these eight functions to specify a cell's new color (lower row) for each possible combination of previous colors of the cell and its two neighbors (upper row).

The significance of universality is also tempered by practicality. Whereas rule 110 (and other cellular automata) can be shown to be universal in principle, in practice it is almost impossible to design the initial condition necessary to perform a desired computation. And even if such an initial condition were known, the time needed to perform the computation might be extremely long compared with that on a traditional computer. Many people have claimed that the concepts of universal computation and uncomputability are relevant to science; in a notable example, Roger Penrose claimed these notions preclude the possibility of machine intelligence (*10*). But I know of no generally accepted scientific explanations or predictions in which these concepts play any role.

Computational Equivalence

The final chapter discusses Wolfram's "principle of computational equivalence," which is based on the idea that the best way to understand processes in nature is to view them as performing computations. It consists of three claims: (i) The ability to support universal computation is very common in nature. (ii) Universal computation is an upper limit on the sophistication of computations in nature. (iii) Computing processes in nature are almost always equivalent in sophistication.

The first claim is plausible, though by no means established. Wolfram's argument is that it is easy to find universal computers even among simple cellular automata. The second claim is also plausible, though supported by less evidence than the first. There are, in principle, processes that can compute things universal computers cannot, but these "super-universal" processes require continuous-valued numbers (*11*). Whether continuous values actually exist in nature and can be harnessed by natural processes to surpass universal computation is unknown. Wolfram strongly believes they cannot. The third claim does not make sense to me. I find it quite plausible that my brain is a universal computer (or would be, if I had infinite memory) and that the brain of the worm *Caenorhabditis elegans* is also (approximately) universal, but I don't accept that the computations we engage in are equivalent in sophistication.

Summary

I think Wolfram is on the right track in proposing that simple computer models and experiments can lead to much progress. This approach may even come to be seen as a new kind of science, though it will be the result of the contributions of a very large number of people—beginning with pioneers of the computer age such as von Neumann, Turing, and Norbert Wiener. (To be sure, Wolfram's own contribution of the *Mathematica* software package has been of great value for such efforts.) I also agree that ideas from the field of computation will be increasingly useful for understanding natural phenomena, particularly in the study of living systems. Nonetheless, analytical approaches to illuminating complexity in nature thus far have been much more successful than cellular automata and related computational methods. A clear example is the successful use of the renormalization group to explain complex behavior in a wide range of dynamical systems (*12*).

Given its length and content, *A New Kind of Science* is surprisingly readable. Wolfram's use of pictures to illustrate difficult concepts works superbly well, and non-scientists will find it possible to understand much of what he covers. The principal obstacle readers face is the plethora of self-aggrandizement, some statements of which seem like they could not possibly be serious. For example, the author claims his principle of computational equivalence "has vastly richer implications...than essentially any single collection of laws in science." Even more disturbing are the suggestions that Wolfram himself invented everything of interest here:

> But to develop the new kind of science that I describe in this book I have had no choice but to take several large steps at once, and in doing so I have mostly ended up having to start from scratch—with new ideas and new methods that ultimately depend very little on what has gone before.

In fact, most of what Wolfram describes is the work of many people (including himself), and most of it was done at least ten to twenty years ago. Nearly no credits to the contributions of others appear in the book's main text. Some credits can be found in the long notes section at the book's end, but many are not given at all. For example, the snowflake models Wolfram discusses are based on the work of Packard (*13*), but Packard is not mentioned in connection with them. This is only one example of such inexcusable omissions. Moreover, the book does not contain a single bibliographic citation—

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Artistic output. Igor Bakshee created this image using rule 110 and *Mathematica*.

CREDIT: (TOP) STEPHEN WOLFRAM; (BOTTOM) IGOR BAKSHEE an astounding lapse that will put off serious scientific readers. Wolfram's Web site (*14*) includes "relevant books," but this list is no substitute.

To benefit from the book, one must get past these issues without becoming too angry and take most of the claims with a large grain of salt. Wolfram's discussions and speculations will interest many people in a wide variety of fields, but they do not constitute a new kind of science.

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15. I am grateful to R. Axelrod, D. Farmer, J. Holland, G. Huber, and C. Moore for discussions and insightful comments on an earlier version of the manuscript and to the Santa Fe Institute for support during the writing of this review.

BOOKS: EVOLUTION

Explanations for the Birds and the Bees

Paul Harvey

If I were an intellectually challenged adult male gorilla who stumbled across an adult male chimpanzee, I should in all likelihood be at a loss to explain my comparatively tiny testicles. Fortunately, my angst might be eased by consulting Dr. Tatiana, the agony aunt, who would point out that large testicles are characteristic of those primates and other mammalian species in which the female often mates with more than one male during a given estrus. Large testicles produce more sperm, thereby providing more tickets in the sperm competition lottery. Female gorillas mate only with the group's silverback who, in the absence of sperm competition from other males, needs to provide just enough sperm to ensure that fertilization is successful. The promiscuous female chimpanzee, on the other hand, has the sperm from different males competing for access to her eggs, so those males have evolved the capacity to produce inordinate quantities of the stuff.

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Dr. Tatiana is the brainchild of Olivia Judson, whose doctoral studies were supervised by the late W. D. Hamilton. She wanted to describe to her audience our current understanding of the evolutionary biology of sex. The topic is manifold, wondrous, and characterized by diversity: Why do some organisms have sexual reproduction whereas others do not? Why do different species have different numbers of sexes? What determines whether individuals are single-sexed or hermaphrodite? Why do some species usually have imbalanced sex ratios while others do not? Why is sex sometimes determined genetically and sometimes environmentally? What are the causes and consequences of the different mating systems seen in the natural world? Over the years the variety has been described and the problems of explaining it have been solved, to varying degrees. Many of the major contributions came from biologists like Darwin who became familiar with the natural history of many, many species and were then able to make comparisons to explain the differences.

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Familiarity with natural history is equivalent to becoming intimate with private lives, except that the former lacks the taboo of anthropomorphism. Some of the best evolutionary biologists work by attempting to identify themselves with the species they study: "What would I do if?" is often useful shorthand for "What would natural selection produce under particular circumstances?" Of course there can be dangers in this way of thinking, which is why formal models often reveal logical pitfalls. But, even then, the results of a logical modeling process need to be described verbally. Judson has gone the whole hog by employing anthropomorphism to its extremes, in the assurance that most of the work she describes has been backed by evolutionary models. Through the device of having organisms describe their situations (and predicaments) to her, she is able to enter a dialog that uses individual case studies to illustrate general principles. This technique draws in the reader to a witty, racy, informed, entertaining, and instructive read.

Dr. Tatiana's Sex Advice to All Creation
by Olivia Judson

Chatto and Windus, London, 2002. 317 pp. £16.99. ISBN 0-7011-6925-7. Metropolitan, New York, 2002. 319 pp. $24, C$34.95. ISBN 0-8050-6331-5.

There will be opposition to Judson's approach. Some will argue that anthropomorphism on this level is unjustified and leads inevitably to inaccuracies. Who cannot feel for the plight of the green spoon worm (*Bonellia viridis*) that just inhaled her "husband"? But, then again, in what sense was the male a husband before being inhaled? Only after being inhaled does the male start to fertilize the female's eggs. This example leads Dr. Tatiana to a description of environmental sex determination in the spoon worm: lone larvae mature into large females and larvae that subsequently develop near a female become male. In a carefully crafted discourse that follows, she explains why and when sex is environmentally versus genetically determined.

It would be wrong to think about *Sex Advice to All Creation* as merely a collection of anecdotes followed by descriptions of general principles. Instead, the book is a developing text, meaning that it should be read from the beginning because answers to some questions require familiarity with earlier chapters. For those who want to check the facts for themselves or to delve more deeply into the problems that Judson tackles, notes at the end of the book cleverly reference the original research papers used in its construction. The bottom line is that the book actually works. Like Richard Dawkins's *Selfish Gene* (Oxford University Press, Oxford, 1976), it uses unabashed anthropomorphism to create scenarios with which the open-minded reader can identify. Also like Dawkins, Judson is a gifted writer, and her book helps further understanding.

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