Wolfram on Cellular Automata; A Clear and Very Personal Exposition

A New Kind of Science

Stephen Wolfram
Wolfram Media, Champaign, Ill., 2002. $44.95 (1197 pp.). ISBN 1-57955-008-8

Reviewed by Leo P. Kadanoff

Early in the 1980s, Stephen Wolfram began to work in earnest on cellular automata, a class of computer model that can be visualized as a set of memory locations, each containing one bit. The bits are updated in a succession of time steps. In each step, the new value of each bit depends on the values of neighboring bits. Wolfram particularly studied the class of automata in which all the bits are arranged in a line, and each bit is updated using the very same functional dependence on its value and that of its two nearest neighbors. There are 256 different automata of that type. Wolfram made it his business to conduct a systematic study of all those different automata using extensive computer simulations, and to think about and generalize from what he thereby uncovered. *A New Kind of Science*, written and published by Stephen Wolfram, is the outcome of those and related studies.

A New Kind of Science is several things at once. First, it is an excellent pedagogical tool for introducing a reader, even one who has no knowledge of advanced mathematics, to some of the concepts of modern computer science, mathematics, and physics. Space-time diagrams of the bits generated by the model show four separate patterns: dull uniformity, periodic time-dependence, fractal behavior, and truly complex nonrepetitive patterns. A discussion of this classification, which I think is originally due to Wolfram, enables the author to introduce modern concepts of complexity. Using these concepts he can discuss fractals (as they were introduced by Benoit Mandelbrot), the idea of universal computation (as it was developed by Alan Turing, Alonzo Church, and others), and the generation of complex patterns in a context in which one can actually see what is going on. The teaching continues with the description of several kinds of computers and of the conceptualization of natural processes as some kind of computation. This is a *tour de force* of clarity and simplicity.

Since the book covers so huge a territory, it should not be surprising to find a few errors in it. For example, in my own area of phase transitions: Wolfram says on page 981 that phase transitions involve a discontinuity in the partition function, and on page 983 that symmetries are usually not important in phase transition problems. Both statements are incorrect. Errors like these will no doubt be ironed out in subsequent editions.

A New Kind of Science is a very personal book. In it Wolfram tells the reader again and again how he discovered some new fact about automata, or used the automata to construct a new illustration of old ideas, or used his knowledge of these systems to construct the beginning of new hypotheses about mathematics or science. These descriptions of the personal events in the development of Wolfram's understanding are valuable both for the insights they give into the science involved and for the revelations they offer about the author himself. This aspect of the book is truly unique.

However, the reporting of history is spotty and sometimes quite weak. That weakness is partially structural, in that the author has not allowed himself any footnotes in the text. Instead, at the back of the book, there are 350 pages of notes that include both history and additional information about the topics in the text; any given topic might be covered in several different places. These notes do not contain any references either; they simply give authors, and sometimes dates. To find original sources one must look up a Web site; I did not choose to do this. Because of this structure, and an overuse of the words "discover" or "discovery," it is hard to distinguish among things that were explained previously by Wolfram and coauthors, well-known things newly explained here in the context of automata, and things that are genuinely new. In fact, the personal nature of the exposition often interferes with the development of full historical descriptions. For example, I did find it interesting that the author devised a partially correct automaton description of hydrodynamic flow in 1973. But I, for one, also find it interesting that a model with some of the same virtues and defects was published by Jack Swift and myself in 1967 (*Phys. Rev.* **165**, 310) and even more interesting that a fully correct model was defined by Uriel Frisch, Brosl Hasslacher, and Yves Pomeau in 1986 (*Phys. Rev. Lett.* **56**, 1595). Wolfram's book does not help one learn these things.

Another structural difficulty arises from Wolfram's use of his own proprietary computer language in place of the usual mathematical notation. Since I am not fluent in the proprietary language, I cannot be sure about the meaning and correctness of the equations used.

The remainder of this review is concerned with the claim the book makes that the author has discovered a "new kind of science." Such a claim is hardly new. One can find it in James Gleick's excellent book *Chaos: Making a New Science* (Viking, 1987). The new science mentioned in *that* popularization also covers, as Wolfram does, topics like the sensitive dependence on initial conditions, the generation of strange attractors and of fractals, the onset of chaos, and complexity. Since neither Wolfram nor the other contemporaneous students of automata are even mentioned in Gleick's book, one might properly doubt that the Wolfram work from the early 1980s could be the new science under discussion.

However, in that era, automaton studies were rather divorced from the main stream of work in chaos and complexity. The leader of the principal automaton group of that period was Edward Fredkin of MIT. His vision is described in the book *Three Scientists and Their Gods* by Robert Wright (Times Books, 1988). This book describes the philosophical and some of

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the technical work Fredkin did and elaborates on thinking that lies at the base of Wolfram's world view. Fredkin especially stressed the idea that everything is a computation, and that the universe is a digital computer. Wolfram is mentioned only once in Wright's book, when disagreements between the two scientists are emphasized. Thus, neither Gleick's nor Wright's independent studies supports possible claims that Wolfram played a major role in making any "new kind of science" in the early 1980s or before.

In his preface, Wolfram says that the new kind of science was discovered in the period since 1991 and brought together in this volume. So we must look for it in the concepts, calculations, and theorems described here for the first time. I found in Wolfram's book interesting things that were new to me. Wolfram mentions (but does not display) a 1994 proof by Matthew Cook that one-dimensional automaton number 110 is a universal computer: It could do any calculation that could be performed by a Turing machine. This unpublished proof identifies a particularly simple automaton example of a universal Turing machine, which I think is the simplest example of such a machine identified so far. Some data included in *A New Kind of Science* were also new to me, especially the counts of the proportion of automata of various kinds that fall into each of the four classes. It is interesting to see how the simplest systems are capable of generating chaos and universal behavior and to see how variation of a parameter could give rise to a transition from mostly repetitive to mostly chaotic behavior. But these data mostly serve to illustrate well-known ideas.

Chapter 9 of *A New Kind of Science*, "Fundamental Physics," contains provocative speculations related to the way automaton models might incorporate quantum theory and gravity—via random network models and path independence. These speculations are, I think, new. The view that the universe is an automaton is due to Fredkin. But, the specific elements in Wolfram's speculation emulate previous two-dimensional quantum gravity theories and earlier work on integrable systems. This chapter describes a partially formed idea—exciting, but not yet science.

The book's longest discussion, in chapter 12, "The Principle of Computational Equivalence," roughly puts all chaotic calculations in the same category. This is a restatement and extension of Wolfram's 1980s idea that classifies automaton outputs into four categories. So far the classification has proved neither subtle nor fruitful.

The remaining apparently new material in the book is speculative and appears to be even less worked out than the examples just mentioned.

From my reading, I cannot support the view that any "new kind of science" is displayed in Wolfram's new book. I see no new kinds of calculations, no new analytic theory, and no comparison with experiment.

Per Bak's book, *How Nature Works* (Copernicus, 1997), covers subjects similar to those of Gleick and Wolfram and looks specifically at automaton studies and at Wolfram. Bak's judgment is that "more than anyone, Stephen Wolfram . . . pointed out that these simple devices could be used as a laboratory for studying complex phenomena." But he also said that "Wolfram never produced any theory of cellular automata." And that is where the subject stands to this day.

Facing Up: Science and Its Cultural Adversaries

Steven Weinberg
Harvard U. Press, Cambridge, Mass., 2001. $26.00 (283 pp.). ISBN 0-674-00647-X

It is almost unfair for me to be reviewing *Facing Up*, a collection of essays by Steven Weinberg, since I consider its author a very important scientist–intellectual. Furthermore, I admire his writing and agree with 99% of his opinions. Happily for this review, the 1% on which we differ is central to this collection and will be discussed at length later.

Facing Up consists of about 20 essays composed over a decade and a half for various occasions, each with a brief preface in which Weinberg describes the inception of the essay and occasionally the response that followed it. More than half of this 250-page book was written for *The New York Review of Books*, with the luxurious length and full airing of controversies typical of that publication. In fact, some of the chapters here are answers to published responses in that journal.

Aside from a few very brief personal essays (Weinberg's opinions on Zionism, an account of the circumstances surrounding his greatest discovery), and one longish discussion of the present state of the science of cosmology, the topics upon which he chooses to divagate are fairly closely related. They define the progressive development of his own scientific philosophy—which for any theoretical scientist must relate to his personal philosophy as well.

Three main themes appear again and again: his own variety of reductionism (where I seem to have been nominated as a "cultural adversary"), his opposition to those who insist that science is socially constructed, and his insistence (to use his words upon being asked to join a dialogue on science and religion) that he is "all in favor of a dialogue . . . but not a constructive dialogue."

In several of the essays Weinberg elaborates on a theme that was central to his earlier book, *Dreams of a Final Theory* (Pantheon, 1992). That book was written as an apologia—in terms of the centrality of elementary particle physics in the scientific world picture—for the enormous expense of the Superconducting Super Collider (SSC).

In one of the essays in *Facing Up*, written for a Newton tricentenary event, he celebrates the standard model (and its possible successors) in physics as embodying the Newtonian ideal of discovering universal laws that apply always and everywhere. Here he sees the progress of science since Newton's time as extending unification to more and more of the world around us, until, at present, we can segue into scientific explanations of all of the facts of nature. So far, one can hardly differ with him. In the earlier book, *Dreams*, he developed the scheme of imagining a chain of "why" questions that would lead from any phenomenon in the observable universe, and end up eventually at the universal laws that reveal the dynamics of the elementary quantum fields composing the universe. "Therefore," he insists, the search for the laws of those elementary fields has some greater intellectual urgency (and may cost more money) than other sciences.

Another essay in *Facing Up*, "Nature Itself," was written as his contribution to the final, overview chapter of the three-volume history, *Twentieth Century Physics* (AIP Press, 1995), edited by Laurie Brown, Abraham Pais, and Brian Pippard. The other contributors to that chapter were John Ziman and myself. In this concise essay he views the century as essentially a grand progress toward the standard model and the Big Bang cosmology, thus ignoring much of the historical material. To my surprise, I learned from the introductory remarks to that essay that he had asked to