

A New Kind of Science

Stephen Wolfram

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Early in the 1980s Stephen Wolfram began to work in earnest upon cellular automata. These are a class of computer model which may be visualized as a set of memory locations, each containing one bit. These bits are updated in a succession of time steps. In each step, the new value of each bit depends upon the values of neighboring bits. Wolfram particularly studied the class of automata in which all the bits are arranged upon a line, and each bit is updated using the very same functional dependence upon the bits at that site and its two nearest neighbors. There are 256 different automata of this type. Wolfram made it his business to study systematically all of these 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 these, and related, studies.

The book, hereafter described as NKS, 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 non-repetitive patterns. A discussion of this classification, which I think is originally due to Wolfram, enables the author to introduce modern concepts of complexity. Using this he can discuss fractals, as they were introduced by Mandelbrot, the idea of universal computation, as it was developed by Turing, Church, and others, and describe the generation of complex patterns in a context in which one can actually see what is going on. 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 a huge territory it should not be surprising to find a few errors in it. For example in my own area of phase transitions NKS

says, incorrectly, 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--again false. Errors like these will, no doubt, be ironed out in subsequent editions.

NKS is a very personal book. Again and again Wolfram tells the reader how he discovered some new fact about automata, or used the automata to construct a new illustration of old ideas, or how he 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 also for **the way** they reveal things 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 three hundred and fifty pages of notes, including both descriptions of history and also additional information about the topics in the text. Any given topic might be covered at several different points. These notes do not contain any references either, they just 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 between things which were explained previously by Wolfram and coauthors, well-known things here newly explained in the context of automata, or things which are genuinely new. In fact the personal nature of the exposition often interferes with giving a full historical description. 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 to know that a model with some of the same virtues and defects was published by Jack Swift and myself in **1968** (Phys. Rev. **165** 310) and even more interesting that a fully correct model was defined by Frisch, Hasslacher and Pomeau in 1986 (Phys. Rev. Lett. **56** 1595). NKS does not help one learn the latter facts.

Another structural difficulty arises from NKS's use of a 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 NKS claim that its author has discovered a “new kind of science.” A “new science” claim is hardly new. One can find it in James Gleick’s excellent 1987 book *Chaos, Making a New Science*. The new science mentioned in *that* popularization also covers topics like the sensitive dependence upon 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 this work, 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 main automaton group of that period was Edward Fredkin of MIT. His vision is described in the 1988 book *Three Scientists and Their Gods* by Robert Wright. This book describes the philosophical and some of the technical work of Fredkin and describes thinking which lies at the base of Wolfram’s world view. Fredkin especially stresses the idea that everything is a computation, and that the universe is a digital computer. In this book, Wolfram is mentioned only once (see page 62) when disagreements between the two scientists are emphasized. Thus **neither Wright's nor Gleick'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 the 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 them in the concepts, calculations, and theorems described for the first time in this book. I found here interesting things that were new to me. NKS mentions but does not display a 1994 proof by Matthew Cook that one-dimensional automaton number 110 is a universal computer so that it could do any calculation that could be performed by a Turing machine. This so-far unpublished proof identifies a particularly simple automaton example of a Universal Turing machine. I think this is the simplest example identified so far. Some data included in NKS **were** also new to me, especially counts of the proportion of automata of various kinds which 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 a mostly repetitive to a mostly chaotic behavior. But these data mostly serve to illustrate well-known ideas.

NKS chapter 9 contains provocative speculations related to how 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 the speculation emulate previous two dimensional quantum gravity theories and integrable systems work. This chapter describes a part-formed idea, exciting.... but not yet science.

The book's longest discussion is devoted to a Principle of Computational Equivalence, which 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 this classification has proven 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 NKS. I see neither new kinds of calculations, nor new analytic theory, nor comparison with experiment.

Per Bak's 1997 book, *How Nature Works*, covers subjects similar to those of Gleick and NKS, 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." (page 106). But he also said on page 107 that "Wolfram never produced any theory of cellular automata." And that is where the subject stands to this day.

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