A Reclusive Kind of Science

Review of *A New Kind of Science* by Stephen Wolfram

Review by David H. Bailey, Lawrence Berkeley National Laboratory

To appear in *Computing in Science and Engineering*

Introduction

If someone had announced that a brilliant, independent-minded scientist had sequestered himself for more than a decade, seldom visiting with colleagues or attending professional meetings, all the time working alone on a "big" project, most of us could sketch out the probable outcome. Indeed, Wolfram's long-awaited tome on cellular automata exhibits characteristics one might expect: encyclopedic in detail and exhaustive in treatment of its topic, but uneven in writing style, a bit brash in tone and sketchy in acknowledgment of others' work.

Before anyone dismisses my review as another instance of Wolfram-bashing, let me first say that I am awed by Wolfram's book. For those of us who have read various titles in the quasi-popular scientific book genre, desperately trying to gain substantive insight into recent developments outside our own specialty, Wolfram's book is a refreshing break from tradition. Just a brief one scan through this 1200-plus page book, which contains 973 beautiful high-resolution graphics, makes it clear that this is not a typical scientific book. It is sobering to realize that Wolfram generated many, if not most of these graphics with his own Mathematica programs.

Wolfram bows to non-expert readers by keeping the body of the text mostly free from potentially intimidating material, but he does include substantial technical detail in the endnotes. Indeed, readers can think of *A New Kind of Science* as two books bound together as one. The first book, approximately 850 pages, attempts to convey the field's outline and flavor to non-scientists (although you could argue that towards the end of this section, such an audience cannot read the book). The second book, approximately 350 pages of small type, fills in many of the gaps left in the first section, including historical background, Mathematica scripts, mathematical arguments, and other more advanced technical material.

Overview

Wolfram's discusses cellular automata — namely, simple discrete processes defined on finite-state systems. He focuses on a class of system that begins with a linear configuration of black and white squares. Thee system then sequentially evolves by changing the color of each existing square based on its previous color and that of its immediate neighbors. There are 256 systems of this particular class. Many of these examples quickly converge to constant or repetitive patterns; others generate interesting but largely repetitive nested structures. However, a few (Wolfram's favorites are Rules 30 and 110) generate endlessly novel patterns.

Wolfram describes other classes of cellular automata (including classes with more than two colors) and 2-D or 3-D examples, but he concludes that none of these classes exhibits

behavior significantly more complicated than the simplest 1-D class exhibits. He concludes that once we pass beyond a certain class of automata that generate repetitive and nested patterns, all such automata are equivalent. In later chapters this notion is extended to a Principle of Computational Equivalence. He demonstrates to the reader via graphics arguments that his Rule 110 is, in the computational sense, universal, like systems such as Turing machines. Wolfram's presentation does not contstitute a rigorous proof that Rule 110 is universal, but in the endnotes he mentions that his associate, Matthew Cook, has achieved a rigorous proof of this fact.

Wolfram spends considerable time discussing connections to numerous fields of science, including artificial intelligence, biology, chaos theory, computer science, consciousness, economics, extra-terrestrial intelligence, fluid dynamics, logic, mathematics, and, of course, physics. The common theme of these excursions is that complicated phenomena may be explained by simple underlying mechanisms. He shows, for example, that simple models based on 2-D cellular automata yield computer-generated "snowflakes" remarkably similar to certain natural snowflakes. In another example, he argues that many crustacean shell types are merely simple variations of a single unsophisticated "program." A third speculation of this sort is that the universe might be a cellular automaton (which Edward Fredkin originally suggested in the 1980s).

Writing Style

Wolfram's high opinion of himself and his work is immediately evident in this book. What can I say about an author who declares his discovery regarding simple mechanisms for complicated phenomena ranks among "the more important single discoveries in the whole history of theoretical science"? In the endnotes Wolfram defends his brashness, explaining that he personally dislikes the self-imposed modesty of most scientific writing. He finds such writing confusing because it is often hard to determine what the author really wants to say. I respectfully disagree — a certain degree of modesty is essential to maintain an atmosphere of objectivity in scientific communication.

There are also some style problems. The books' main text has choppy, one- and two-sentence paragraphs, with an annoyingly large fraction of these sentences starting with "And," "So," or "But." As before, Wolfram defends this style in the endnotes, explaining that this style is esential to split up otherwise lengthy sentences and paragraphs. Additionally, readers will likely find the main text of the book to be repetitive. For example, Wolfram repeats dozens of times the mantra that simple systems can generate complicated phenomena.

Curiously, the endnotes are much better written than the main text. Paragraphs are coherent, and the exposition is significantly tighter than the first part. It is as if a different author had written this part.

Attribution

Wolfram does not include references or a bibliography in the book. This is already a topic of controversy in the scientific community, as some scientists feel that Wolfram

has appropriated other scientists' work. Other scientists have complained that he has not fully acknowledged their contributions, or that he mentions only one researcher involved in a discovery when several should be mentioned. In Wolfram's defense, it appears that many of his critics have not read the endnotes, where he mentions many key contributors. However, the lack of a bibliography remains a significant and puzzling deficiency.

Wolfram's Central Point

Wolfram's defenders have responded to these criticisms by arguing that we should focus on Wolfram's scientific contributions in the book, not on relatively superficial issues. Accordingly, I will now turn to such matters.

Wolfram's central point in the book is that complex behavior does not require complex systems; instead, simple systems can generate substantial complexity. He states this point repeatedly, as if attempting to convince recalcitrant scientists who otherwise would never accept such a controversial proposition. Who are these scientists? I certainly do not find Wolfram's point controversial. I can cite numerous examples of this principle, some of which have been known for many years.

An example is the notion of normal numbers in mathematics (which Wolfram briefly mentions in the endnotes). A real number is said to be normal base b if its base-b digit expansion has the property that every m-long string of digits appears with precisely the limiting frequency, namely b^{-m}, which we would expect of a "random" expansion. It is a well-known, if counterintuitive, fact of measure theory, first proven in the early 1900s, that almost all real numbers are normal base b for all bases b. Furthermore, it is widely believed, although not proven, that all of the classical constants of mathematics, including π, e, $\sqrt{2}$ and $\log 2$, are in this category. We can even conjecture that every irrational algebraic number is normal, because there are no known or suspected counter-examples. In short, from measure theory and the theory of normal numbers, it is clear that random-looking, complex behavior is the norm — orderly behavior is exceptional.

As another example, consider the recently discovered iterations [1] that generate digits of certain mathematical constants. For example, the simple iteration $x_0 = 0$, and

$$x_n = \{2x_{n-1} + 1/n\}$$

(where $\{\}$ denotes fractional part) generates the binary digits of $\log 2$ with progressively greater fidelity, by noting which subinterval, $[0, 1/2)$ or $[1/2, 1)$, each successive iterate lies in. A similar sequence that generates hexadecimal digits of π is given by $x_0 = 0$, and

$$x_n = \left\{ 16x_{n-1} + \frac{120n^2 - 89n + 16}{512n^4 - 1024n^3 + 712n^2 - 206n + 21} \right\}$$

Note that in both of these instances the starting point is zero, so that the "random" behavior of the iterates is certainly not rooted in the initial conditions; instead it is inherent in the iteration definition itself.

A third example is the well-known "logistic" map of chaos theory, namely the simple iteration

$$x_{n+1} = rx_n(1 - x_n)$$

(this is briefly mentioned in the endnotes of Wolfram's book). For values of r in the range $1 < r < 3$, iterates converge to a single limit point. For $3 < r < 3.44$, iterates alternately visit the neighborhood of two distinct limit points. For slightly larger r, there are four limit points, then eight, etc. Finally, for r in the range $3.57 < r < 4$, all periodicity disappears — the iteration is completely chaotic. Furthermore, this chaotic nature is a fundamental characteristic of the iteration itself, not of initial conditions. As before, this is not a new observation — it has been known for 40 years (as Wolfram acknowledges), yet it is a good example of his principle.

Wolfram might counter that the above examples are based on the mathematics of the continuous real line, and that in a computer implementation, finite-precision arithmetic results in distinct behavior. However, we can make the same comment about cellular automata. They also require finite registers for real-world implementation (as he acknowledges), and these finite-register automata are distinct from the idealized examples. In this sense, we can regard Wolfram's chaotic cellular automata, as implemented on finite-register computers, as merely a new class of pseudo-random number generators. One of these schemes is in fact used as a pseudo-random number generator in Mathematica.

Not Rigorous Enough

A second fundamental criticism of this book is that all too frequently one reads phrases such as "It seems clear to me" and "I suspect that" in the place of rigorous scientific arguments. Many of Wolfram's arguments in the natural sciences are not impressive.

For starters, I am disappointed in Wolfram's Principle of Computational Equivalence. After several chapters of relentless buildup, readers expect at least a rigorous statement of this principle. But Wolfram declines to provide such a statement, preferring instead to rely on intuition.

In the evolutionary biology section, Wolfram asserts that simple programs underlie at least part of the complexity that we see in the biological world. He gives a number of examples, such as sea shells that appear to be minor variations on a simple program, but biologists have already presented similar examples, for example in Richard Dawkins' books [2, 3].

Wolfram mentions applying cellular automata to fluid dynamics, giving some graphical examples that he personally generated, but this too is not new. I saw Wolfram give such a demonstration on an early Connection Machine in 1986. He claims that these cellular automata-based simulations are now gaining greater acceptance, but I am not aware of any fluid dynamicists who concur. To the contrary, Navier-Stokes-based schemes are the methods of choice in almost all practical fluid dynamics simulations today.

As I mentioned above, Wolfram argues that the universe itself may be a cellular automaton at some level, a notion first suggested in the 1980s. After all this time, you might be inclined to think that Wolfram surely has some significant, new results here. He does mention some interesting ideas, but he does not provide a clearly falsifiable test — much less proof — of this hypothesis.

Advantages of the "System"

I began my review by stating that *A New Kind of Science* exhibits several weaknesses that you might expect from a reclusive, one-person effort. Perhaps there is a lesson here. The traditional collaborative method of doing science, which Wolfram evidently dismisses, has distinct advantages.

The publishing system results in peer-reviewed journals and conference proceedings — it has the important advantage of establishing a clear "paper trail" of idea ownership. Because of this system, squabbles over priority are almost always nipped in the bud, and cooperation, collaboration and goodwill between scientists are greatly facilitated. Additionally, it significantly improves the quality of published work.

The established system of scientific conferences and journals also helps to separate research that is worth doing from research that is not. If a paper is not accepted at a conference, even if it is technically sound, maybe that is a cue to the researchers that the ideas presented (or even the overall topic) are not very interesting to the community, so that perhaps they should redirect research efforts to other questions.

With regards to *A New Kind of Science*, I would argue that to the extent that cellular automata in general, and Wolfram's study of cellular automata in particular, constitute fruitful, promising avenues of research, they deserve to be studied by more than a solitary scientist, however great his talents and resources may be. A larger community in the field could bring to bear many different types of expertise that Wolfram lacks, especially expertise in allied fields such as biology and human consciousness.

Why hold your research so tightly to the chest? If you have great ideas, let others share in the joy of discovery and the triumph of success.

References

[1] David H. Bailey and Richard E. Crandall, "On the Random Character of Fundamental Constant Expansions," *Experimental Mathematics*, vol. 10, no. 2 (June 2001), pg. 175-190.

[2] Richard Dawkins, *The Blind Watchmaker: Why the Evidence of Evolution Reveals a Universe Without Design,* Norton, New York, 1996.

[3] Richard Dawkins, *Climbing Mount Improbable*, Norton, New York, 1997.