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Stephen Wolfram: A New Kind of Science-or a Not-So-New Kind of Computer Program?

IN MAY 2002, AFTER SPENDING A DECADE living as a recluse, the legendary Stephen Wolfram stepped into the public arena with the publication of a book promising to revolutionize the way we do science. For hundreds of years, scientists have successfully used mathematical equations that show how various entities are related. For example, Newton's equation (his second law of motion)  $F=ma$  shows us how force (F) is related to mass (m) and acceleration (a). The problem with this approach is that equations fail to adequately describe complex phenomena all around us, such as the turbulence of boiling water or the changing weather. Whereas equations cannot capture such complexity, Wolfram believes that simple computational rules can. Therefore, to model nature's complex phenomena, Wolfram proposes that scientists give up their unwieldy equations and instead employ the types of computational rules used in cellular automata (CA) and related computer programs. These programs repeatedly execute a set of Riles that are simple enough for a child to follow. Yet, despite their ultimate simplicity, these programs can generate immense complexity.

According to Wolfram, the discovery that simple rules can generate complexity-a discovery he attributes primarily to himself-is "one of the more important single discoveries in the whole history of theoretical science."<sup>1</sup> The reason he believes this discovery is so important is that it applies to everything in the universe. Computations are not just performed by the chips in our computers. Rather, every physical process, from an exploding star to water swirling down a drain, can be viewed as a series of computations or programs in which the process moves, moment by moment, from some initial state to some outcome. So instead of using equations to describe some of the regularities seen in nature's programs, Wolfram tells us to examine the programs themselves.

A Jedi Mind-warrior

Wolfram is a genius among geniuses, or as Wired reporter Steven Levy says, a "Jedi mind-warrior." Wolfram's brilliance became apparent at an early age. He earned a scholarship to Eton College at age 13. At 15, he published his first scientific paper, a study in high-energy physics titled Hadronic Electrons? In 1978, the renowned physicist Murray Gell-Mann invited Wolfram to the California Institute of Technology (Caltech), where within a few years he published more than 25 scientific papers. The work he did during his first year at Caltech earned him a doctorate in theoretical physics when he was just 20. At 21, Wolfram became the youngest scientist to receive a MacArthur award for his work in physics and computer science.

At Caltech, Wolfram become interested in explaining how complex structures like galaxies evolved. He gradually became convinced that mathematics was not up to the task. The equations of mathematical physics can describe relatively simple phenomena, but not phenomena as complex and messy as the evolution of galaxies, the dynamics of weather, or the fluctuations of the stock market.

After a feud with Caltech over the rights to his work, Wolfram transferred to the Institute for Advanced Studies at Princeton. At Princeton, Wolfram gained access to powerful computers, which he used to perform computer experiments. These experiments led him to the idea that CA and related systems could revolutionize the way we do science.

Despite Wolfram's brilliance, he never adjusted to academic life. He left Princeton, and after a short-lived stint at the University of Illinois, founded his own company, Wolfram Research, Inc. Within a few years, Wolfram made a fortune developing "Mathematica"-a powerful software program that has become a standard for technical computing. Unlike some successful entrepreneurs, Wolfram never lost interest in fundamental science. With his newly found financial independence, he spent a decade or so working in relative isolation at home.

Wolfram performed numerous computer experiments and captured his ideas in his book, A New Kind of Science (NKS), which grew to an impressive 1,197 pages. This book revealed the results of his research on CA and related fields. Unlike most books of such Brobdingnagian size, Wolfram's tome was an immediate success. It briefly made Amazon.com's best-seller list, along with less weighty works such as the Divine Secrets of the Ya-Ya Sisterhood. Wolfram's book was reviewed in many popular publications, including the New York Review of Books, Forbes, Le Monde, Wired, Time, Newsweek, Business Week, the Guardian, and the Telegraph.

How can a massive book dealing with computer programs and science become such a sensation? As Jordan Ellenberg, assistant professor of mathematics at Princeton, reflected, "Wolfram is selling not just a theory, but a story-the story of a genius who retreats from the misunderstandings and jealousy of smaller minds." This story resembles the narrative of A Beautiful Mind. In a New York Times book review, for instance, George Johnson captures this theme: "For more than a decade, Wolfram. . .has been

laboring in solitude on a work that, he has promised, will change the way we see the world. . . ignoring the bad vibes and hexes cast by jealous colleagues hoping to see him fall flat on his face."

### Cellular Automata

To help understand why Wolfram believes a new kind of science is needed, let's begin, as Wolfram does, with cellular automata. CA are systems in which cells that are laid out in a regular spatial grid change color (state) according to rules that depend on the color of the cell and its nearest neighbors. By applying the same simple rules over and over again, CA can generate a wide variety of patterns, some of which are highly symmetric like snowflakes, others that appear random, and others that look basically the same on all scales (fractals). Wolfram discovered that even the simplest CA could yield patterns of astonishing complexity. (Wolfram views complexity in terms of how patterns are perceived rather than how they are created.)

#### IMAGE ILLUSTRATION

The 16th century imagined the hidden mechanics that governed the universe as a series of spheres. We have replaced the original spheres in this famous German woodcut with patterns that suggest Stephen Wolfram's experiments. To view Wolfram's discoveries as shown in his book *A New Kind Of Science*, and to find out how to run the same experiments on your own computer go to [www.wolframscience.com](http://www.wolframscience.com).

#### IMAGE ILLUSTRATION

Figure 1-A representation of rule 110.

Figure 2-Fourteen rows following rule 110.

To illustrate CA, grab a sheet of graph paper and a pencil. Each little square on your graph paper represents a "cell." Use your pencil to blacken just one square in the top row, a few squares from the right edge of the sheet. Now move to the second row of cells. Blacken the cells of the second row according to a simple rule, such as the following: For each cell in the second row, examine the three neighboring cells on the row above it—the one directly above, and the ones to its upper-left and upper-right. If these three upper-row cells are all black or all white, or if only the upper-left cell is black, leave the current second-row cell white; otherwise, blacken it.<sup>2</sup> This rule is illustrated in Figure 1, which shows the correct color for the bottom cell, based on all possible color combinations of its three upper neighbors.

When you are finished applying the preceding rule to all the cells in the second row, move to the third row. Apply the same simple rule to each cell in the third row, now using its three neighboring cells in the second row. Repeat this process, row by row, where the colors of each row of squares depend on the colors of the previous row, until you have either worked your way down to the bottom of the sheet of graph paper or worked your way to a state of exhaustion. Now stand back and gaze at your creation: a sheet of paper covered by a pattern of black and white squares. After filling in 14 rows, you should get the pattern shown in Figure 2. The pattern you just created emerges from a simple CA that follows one of the 256 possible rules delineated by Wolfram, in this case, rule 110.<sup>3</sup>

Some people might ask, "but is it art?" For Wolfram, this pattern of black and white squares is far more than just a pretty picture resembling Mondrian's "Broadway Boogie." CA are for Wolfram what finches were for Charles Darwin. They triggered a realization. Wolfram became convinced that patterns generated by simple programs underlie most of the complexity seen in nature—from the air turbulence generated around the wing of an aircraft, to the art deco-like design on some seashells, from the ups and downs of the stock market, to the intricate workings of our brains. Wolfram even perceived the universe itself as a gigantic computer, playing out its simple rules to create the immensity of space, time, and everything within it. In the end, asserts Wolfram, "it will turn out that every detail of our universe does indeed follow rules that can be represented by a very simple program—and that everything we see will ultimately emerge just from running this program."<sup>4</sup>

After hearing such extraordinary claims, one might infer that all the years Wolfram spent squinting at the billions of tiny black and white cells on his computer screen rendered his grasp of reality a tad flimsy. Perhaps Wolfram is hallucinating, seeing CA everywhere he looks. Otherwise, how could anyone claim that CA has such cosmic significance?

To answer this question, let us see the pattern generated by rule 110 after going down thousands of rows. It may seem that pursuing such an inquiry would demand as much effort as painstakingly scrubbing the tar off the ancient bones found in the La Brea Tar Pits. With the advent of computers, however, such an inquiry can be carried out with great speed and perfect accuracy. In Wolfram's book, pages 32 to 38 show what rule 110, starting with a single black square in the top row, looks like after going down thousands of rows. A pattern emerges with a remarkable mixture of regularity and irregularity. What Wolfram finds so amazing about such CA is how simple rules can generate extremely complex patterns. This observation seems to defy our common-sense notion that only complexity begets complexity. If, for instance, you saw an extremely intricate design on a stained-glass window or carpet, you would reasonably conclude that much painstaking effort had been taken in creating it. If you saw an enormously complex machine, such as the Space Shuttle or a linear accelerator, you would justifiably conclude that engineers spent many years designing and integrating all its complex components. Thus, experience tells us that the more intricate the artifact, the more complex the process used to create it.

Rule 110, however, defies common sense. Without knowing about this rule, imagine having to describe the immensely complex pattern it generates. Imagine that your description has to be so good that other people can duplicate the pattern in all its exacting detail from your description alone. This task would seem overwhelming because there is no trace of its humble rule-based origin. It seems that a description of this pattern would have to be about as complex as the pattern itself. How astonished and relieved you would be if Wolfram came along and showed you that this immensely complex pattern could be simply described as rule 110.

Starting with a single black square and then applying the same trivially simple rule over and over again created the complex pattern of rule 110. (Alternatively, one can create an arbitrarily complex pattern by starting with multiple black squares.) No randomness or complexity was injected from outside the system. So where does such complexity come from? As Wolfram points out, in some mysterious manner, we seem to be "getting something from nothing."<sup>5</sup>

Wolfram argues that patterns such as those generated by rule 110 are "computationally irreducible." To determine whether a particular square, say on the 1000th row, is black or white, one must run the computer program and see what happens. One cannot predict in advance what the color of the square will be. There is no shortcut available, such as an equation, to provide the answer.

Wolfram argues that many complex systems in nature, like rule 110, are computationally irreducible. Like Heisenberg's Uncertainty Principle or Godel's Incompleteness Theorem, the notion of computational irreducibility places fundamental limits on what, in principle, can be known. It implies that the behavior of many complex systems in the universe, by their very nature, cannot be predicted. CA and related programs, however, might be used to describe and understand these systems.

According to Wolfram, rule 110 is not only computationally irreducible, it can also act as a universal computer, performing any calculation that any computer, even the jazziest PC or Macintosh, can perform. Thus, given the correct input-blackened squares on the top row-and the requisite number of iterations of the rule, anything that is capable of being computed could, in theory, be computed. One might have to begin with many blackened cells and run the rule many millions of times, but eventually the correct output could, in principle, be obtained. If something as basic as rule 110 can exhibit universality, the natural world must be full of other examples.<sup>6</sup>

Universal computers are computationally equivalent. Each computer can calculate whatever the others can, and each can simulate the behavior of any other. If, for instance, two CA are universal, then, starting with the correct arrangement of black squares in the first row, one CA can generate the same pattern generated by the other CA.

Is this Pseudoscience?

Wolfram's flawless credentials, staggering intelligence, and depth of knowledge strongly suggest that he is no crank-not someone whom skeptics would dismiss as a pseudoscientist. Yet skeptics will notice that Wolfram displays many attributes associated with being a pseudoscientist: he (1) makes grandiose claims, (2) works in relative isolation, (3) bypasses the normal peer-review process, (4) published his own book, (5) does not adequately acknowledge the contributions of his predecessors, (6) rejects or belittles the work of eminent scientists, and (7) reinterprets criticism as support. The late Nobel laureate Steven Weinberg remarked that the grandiose claims and other antics exhibited by Wolfram would normally prompt him to place the book "on the crackpot shelf" of his bookcase. But, he admits, "in the case of Wolfram's book, that would be a mistake." Let's examine each of the seven attributes of a pseudoscience, keeping Weinberg's warning in mind.

#### (1) Makes Grandiose Claims

It is hard to imagine any claim more grandiose than that of Wolfram. His audacity is captured in the book's title: *A New Kind of Science*. Instead of advancing scientific understanding in a particular discipline, Wolfram claims to provide a new way of practicing science itself. If the scientific community embraces this new kind of science, it would be the greatest paradigm shift since Isaac Newton showed how equations could be used to express universal laws of nature. This comparison with Newton is not lost on Wolfram. In his Preface Wolfram states, "Three centuries ago science was transformed by the dramatic new idea that rules based on mathematical equations could be used to describe the natural world. My purpose in this book is to initiate another such transformation, and to introduce a new kind of science that is based on the much more general types of rules that can be embodied in simple computer programs." In a 1995 telephone interview, Wolfram assured former *Scientific American* correspondent John Morgan that this new science would be the biggest thing since Newton's discoveries. When Horgan asked why Newton, why not Einstein? Wolfram replied that his ideas were even bigger than Einstein's.<sup>7</sup>

In his Preface Wolfram states that his new kind of science "touches almost every existing area of science, and quite a bit besides." Later in the Preface he continues, "Yet in time I expect that the ideas of this book will come to pervade not only science and technology but also many areas of general thinking. And with this its methods will eventually become a standard part of education-much as mathematics is today."

With this new kind of science, Wolfram claims, "it suddenly becomes possible to make progress on a remarkable range of fundamental issues that have never successfully been addressed by any of the existing sciences before."<sup>8</sup> He claims these fundamental issues include the randomness found in the universe, biological complexity, the nature of space and time, a "theory of everything," and the scope and limitations of mathematics. Wolfram even claims his insights can be used to tackle the ancient paradoxes of free will and determinism, and the nature of intelligence.

Regardless of the merits of Wolfram's book, many readers find Wolfram's extravagant claims to be highly offensive. This view has spawned many nasty jokes, especially on the Internet. Some readers suggest that, despite its imposing weight, Wolfram's book should not be tossed aside lightly, but thrown with great force. Wolfram has been called the "Britney Spears of science" and has been described as the mathematics guru who united the "fields of mathematics, physics, biology, chemistry, and mini-golf." Zack Unlocker, on the website "From Valley of the Geeks.com," claims that at 15, Wolfram published his first paper, "Why I'm Smarter than Einstein," and at 21 received a MacArthur Fellowship genius award "for arrogance." David Brunton illustrates how witty comments about CA can liven up an otherwise boring cocktail party. For instance, consider this line: "You'd be amazed how easily this [the drink you are holding] goes straight down. Of course, it's not too surprising, since rules 4, 12, 36, 68, 76, 100, 108, 132, 140, 164, 172, 196, 204, 228, and 236 of Wolfram's binary cellular automata all yield a straight-down pattern." After reading Wolfram's book, Pete Fermat, a student at "Podunk" Community College, could hardly contain his excitement. "The most significant revelations in human history are contained in a book inaccessible to people without an advanced degree and high-end computer power. I bet everyone who beat me up in junior high school is sorry now. Math touchdowns for everyone!" And finally, a reader from Los Angeles posted on Amazon.com, "Reads like propaganda for a hostile takeover of science from a CEO."

#### (2) Works in Relative Isolation

In his preface Wolfram writes, "I have for most of the past decade been an almost complete recluse, attending almost no outside events, and interacting mainly just with my family, friends, assistants and senior staff at my company." During this decade of isolation, Wolfram spent almost all his time performing computer experiments and writing his book. Wolfram estimates making 100 million keystrokes and moving his computer mouse more than 100 miles. So why did Wolfram hide his work from professional scrutiny? In a *New York Times* interview, Wolfram offers a blunt explanation: "A lot of people find that in doing something like science, it's useful to interact with lots of other people." But, he avers, "as I went further along, I realized that the kind of stimulation that one gets from talking to other people about what one is doing I didn't really need." Why not? To a *Wired* magazine reporter Wolfram explained, "[M]y opinion of the world at large isn't high enough for me really to be interested in what they [critics] have to say."

#### (3) Bypasses the Normal Peer-Review Process

Wolfram admitted at a Caltech panel symposium on his work (in February 2003) that over the last decade he accumulated enough material for hundreds of scientific papers, yet he did not bother to publish anything or to present any of his ideas at scientific conferences. Thus, Wolfram did not benefit from the traditional collaborative method of doing science. In particular, he forfeited any critical feedback that might have improved his work before it was cemented in inky stone. He also lost the opportunity to establish a paper trail of ideas to reduce the likelihood of disagreements over who originated which ideas.

So why did Wolfram work for a decade without publishing his findings as he went along? "I gradually came to realize," he recalled, "that technical papers scattered across the journals of all sorts of fields could never successfully communicate the kind of major new intellectual structure that I seemed to be beginning to build. So I resolved just to keep working quietly until I finished, and was ready to present everything in a single coherent way. Fifteen years later this book is the result."

#### (4) Published His Own Book

Wolfram published NKS himself, not because he could not get a publisher, or because no publisher would print such a massive book. Recall that Stephen Jay Gould's magnum opus, *The Structure of Evolutionary Theory*, was released at about the same time by Harvard University Press, topping out at 1,433 pages. Between these two books, bookstores shelves were sagging under the weight of Big Science. Wolfram self-published because he wanted to maintain tight control over the production and distribution of his life's work. This method of proceeding is in keeping with Wolfram's general desire to control the process of give and take with the scientific community and the world at large. Even Newton, who like Wolfram spent years in isolation before delivering his revolutionary *Principia*, nevertheless published his book with an unassuming scientific title and used a mainstream scientific publisher.

#### (5) Does not Adequately Acknowledge the Contributions of his Predecessors

Many scientists complain that Wolfram fails to acknowledge the work of other scientists. Brian Hayes, senior writer for *American Scientist*, states, "The problem is not just the rosy spotlight that Wolfram shines upon himself at center stage; it's also the utter darkness that enshrouds all the other actors in this drama." Computer scientist, mathematician, and chairman of Webmind, Inc., Ben Goertzel, remarks, "There is an irritating density of passages in which the author takes personal credit for ideas that are 'common knowledge' among experts in the relevant fields." CA pioneer Edward Fredkin allegedly said that Wolfram is "incompetent at giving people credit."

NKS lacks traditional references to scientific papers and books on related topics. It contains no bibliography. The first preface offers no thanks to friends or colleagues. In the second preface, printed in a tiny font, Wolfram grants, "Over the course of the past twenty years I have learned many things relevant to this book from many people." He then provides a laundry list of people with few specifics. The main text mentions few scientists by name. All history and acknowledged contributions of other scientists have been relegated to a 349-page section of "General Notes" in the back of the book, but are not referenced at all in the main text. Even so, these general notes consist mostly of additional commentary on Wolfram's own work, with only an occasional reference to other scientists, but rarely citations of their work.

Although Wolfram is careless about giving proper credit to others, he is very careful about receiving credit. The copyright notice of his book says, "Discoveries and ideas introduced in this book, whether presented at length or not, and the legal rights and goodwill associated with them, represent valuable property of Stephen Wolfram, LLC, and when they or work based on them is described or presented, whether for scholarly purposes or otherwise, appropriate attribution should be given."

#### (6) Rejects or Belittles the Work of Eminent Scientists

Lawrence Gray, professor of mathematics at the University of Minnesota, states, "Wolfram loves to tell us why other scientific theories cannot handle complexity. But in these discussions, he badly mischaracterizes his competition." According to Gray, "He is particularly hard on chaos theory, which he more or less reduces to a trivial observation about sensitive dependence on initial conditions."

One of Wolfram's favorite ploys is to serve up some choice example of nature's creation, such as a snowflake, whose formation, he claims, scientists have been at a loss to explain. Wolfram then gloats over how his CA provide the much needed explanation. As Phillip Ball, freelance science writer and consultant editor of *Nature*, points out, many of the examples Wolfram produces have been adequately explained by the equation-rich theories that Wolfram discounts. For instance, researchers at Caltech, such as Kenneth Libbrecht, have adequately explained how snowflakes form, and have even engineered "designer" snowflakes, with patterns of their choosing.

Wolfram even belittles the work of the great CA pioneers, such as John von Neumann and John Conway, who, Wolfram claims, failed to connect their work to basic science.<sup>9</sup> According to Wolfram, von Neumann "presumably never imagined" that CA as simple as Wolfram's one-dimensional variety could exhibit complex properties such as self-reproduction. And Wolfram asserts that Conway did not take his work seriously enough, but treated it "largely as a recreation." According to Wolfram, Conway also failed to systematically investigate the wide range of possible rules.

At the 2003 Caltech symposium, Wolfram raised the hackles of the scientific panel as well as the audience when he belittled one of the most famous scientists of all time—Charles Darwin. Although Wolfram does not claim natural selection is totally without merit, he does claim it is insufficient to fully explain the complexity found in the biological world. For instance, he claims that natural selection can explain phenomena such as the lengthening of bones, but not fundamental changes to an animal's morphology. (As an aside, Wolfram's doubts about Darwinian natural selection should hardly comfort Creationists. Wolfram's new kind of science is a Creationist's worst nightmare. Where natural selection only provides a naturalistic explanation for biological complexity, Wolfram's theory provides a naturalistic explanation for every type of complexity, including, Wolfram argues, human intelligence and the universe itself.)

#### Reinterprets Criticism as Support

Many pseudoscientists think their ideas are so revolutionary that criticism of their theory paradoxically validates it. After all, the establishment always resists paradigm shifts. Wolfram shares this skewed view. Caltech physicist Steven Koonin, who moderated the Caltech symposium, asked the panelists to predict whether in 20 years Wolfram's new kind of science would be viewed as a paradigm shift. The unanimous answer was "no." One panelist said, "It is not an approach that has much promise," while another

asserted that Wolfram's ideas are the "Emperor's New Clothes." Wolfram tried to get in the last word by stating that this reaction from the panelists is just what one would expect from a paradigm shift. But Koonin rejoined that this is also what one would expect if Wolfram's ideas did not amount to a paradigm shift. This exchange produced the lightest moment of the day. Ultimately, time will tell who is right.

On National Public Radio, Wolfram argued that scientists ignore those who falsely claim to have made a paradigm shift, but get upset by those who really do so. Thus the negative reaction of scientists is a validation of his claims. A more plausible explanation for this negative reaction, however, is the manner in which Wolfram refuses to play the role expected of serious scientists.

What is New?

Many critics have argued that Wolfram's purported new kind of science is neither new nor science. Let us begin by considering whether Wolfram's ideas are new.

In the Preface of NKS, Wolfram states, "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." Few, however, share this assessment. Many critics claim that Wolfram's new science is actually quite old. Wolfram's "'new kind of science,'" asserts Goertzel, "is none other than the science of complex systems, which has been growing for some time." Or as Leo Kadanoff, professor of physics and mathematics at the University of Chicago said, "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." Mathematician Edwin Clark from the University of South Florida notes, "Despite the title, most of the science in ANKOS [NKS] will be new only to readers unaware of the CA field."

Evaluating the originality of all the ideas Wolfram claims are his is a daunting task. I will briefly point out a few of Wolfram's important predecessors.

The great mathematician John von Neumann developed CA in the early 1950s at the suggestion of physicist Stanislaw Ulam. Von Neumann was especially interested in the way structures could reproduce.

If Wolfram's CA seem familiar, you probably encountered a dangerously addictive two-dimensional version called Life or the Game of Life. (This automaton is two-dimensional because the color of each square depends on the color of its surrounding eight neighboring squares, not just the three squares above it.) Mathematician John Conway developed Life in the 1960s. After Martin Gardner featured Life in his "Mathematical Games" column in the October 1970 and February 1971 issues of Scientific American, it became the latest rage among computer buffs. Across the country, computer screens appeared to be infected by strange cyber creatures skittering about, reproducing, evolving, and competing for the limited screen space. According to Forbes science writer Michael Malone, Wolfram was introduced to Life while in high school, and wrote a program implementing Life. Obviously, this experience had a lasting impact on Wolfram and clearly showed him how simple programs can generate great complexity. (Conway's Life and at least one of Neumann's rather complex CA-involving 29 colors-turned out to be universal computers.)

If you are not familiar with Life, then perhaps you have seen calendars and posters featuring the beautifully complex patterns called fractals, discovered by mathematician Benoit Mandelbrot. Mandelbrot showed that from simple algebraic descriptions a stunning richness of detail emerges that can be examined at smaller and smaller scales.

Even Wolfram's main thesis is not new: that simple programs govern complex systems, including the universe itself. In the 1982 book, *Winning Ways for Your Mathematical Plays*, Conway made this Wolfram-esque observation: "Life is Universal!...It's remarkable how such a simple system of genetic rules can lead to such far-reaching results." Conway even mused that we may be like Life's cyber creatures, unknowingly playing out our CA-like rules on a grid of enormous proportions. The CA pioneer Tommaso Toffoli, and Nobel physicist Richard Feynman, made similar observations. According to George Johnson, Toffoli said, "In a sense, nature has been continually computing the 'next state' of the universe for billions of years." And according to Weinberg, Feynman suggested that the universe is an automaton, like a giant computer, as far back as 1981. Even earlier, in 1964, Feynman said, "ultimately physics will not require a mathematical statement, that in the end the machinery will be revealed, and the laws will turn out to be simple, like the chequer board with all its apparent complexities."<sup>10</sup> Interestingly, Wolfram worked with Feynman during his days at Caltech.

Arguably, the person who should be given the greatest credit for Wolfram's core ideas is Edward Fredkin, former head of MIT's Laboratory for Computer Science and currently a visiting scientist at MIT's Media Lab. Fredkin began seeing the universe as a digital computer in the 1950s and started publishing papers about it around 1980. Seeing the universe as a computer, stated Fredkin, "might be the beginnings of a new intellectual revolution comparable to what was spawned by the development of mathematics."

According to Fredkin, at a physics of computation conference on his small Caribbean island about 20 years ago, he proposed to Wolfram that the universe operates like a CA. Wolfram "wouldn't buy into it," Fredkin says, and during a subsequent encounter, "he described my ideas as crazy." And Fredkin's ideas may actually be crazy. According to the San Francisco Chronicle science writer Keay Davidson, "Fredkin said that he's open to the possibility that our reality is an illusion on some alien creature's computer." To paraphrase Woody Allen, that reality is an illusion is a pretty uncomfortable thought, particularly if you've just made a down payment on a house.

Although Fredkin is justifiably irked at not receiving proper credit for his ideas, he nevertheless views the publication of NKS as "a great event." Fredkin reportedly said, "Wolfram is the first significant person to believe in this stuff. I've been very lonely."

On balance, Wolfram's "new kind of science" may be best described as a "not-so-new kind of computer program." Perhaps what is new in NKS is the way Wolfram musters so many facts about simple programs to back up his claim that CA and their close relatives, instead of being peripheral to science, should be central to the way science is practiced.

Is this Science?

In addition to challenging the newness of Wolfram's claims, some critics have questioned whether Wolfram's new science is even science. Although Wolfram's work is not pseudoscience, it does not follow that it is science. It is possible that Wolfram's work is neither science nor pseudoscience, but something more akin to mathematics, game theory, or philosophy. The renowned

physicist Freeman Dyson told Wired magazine, "I'm not sure that what he [Wolfram] does can be called science. It's more in the nature of mathematical games. He clearly is not a physicist anymore." Similarly, Washington University mathematics professor Steven Krantz said, "I am not yet convinced that they [CA] tell us much of anything about science." Perhaps the best way to address this issue is to compare Wolfram's new science with what he calls "traditional" science.

### Balancing Observation with Theory

As Michael Shermer points out in his April 2001 "Skeptic" column in Scientific American, modern science is an exquisite blend of observation and theory. Observed facts do not speak for themselves; they must be interpreted through ideas. Before the advent of modern science, however, the blend of observation and theory was often woefully out of balance. Many thinkers devalued observation and attempted to fathom the deep mysteries of the cosmos through thought alone. Just think hard enough and deep enough and nature's secrets would reveal themselves. In some ways, Wolfram's book seems like a throwback to this prescientific era, although instead of armchair theorizing, Wolfram engages in computer chair theorizing. For Wolfram, the computer becomes an extension of his mind. With little delay, he can see the results of his programs evolve on the screen as their simple rules are played out innumerable times with perfect accuracy. For over a decade, Wolfram performed countless such computer experiments, yet never performed any laboratory experiments. Wolfram's anti-empirical antics prompted Davidson to remark: "Once dismissed as a relic of the Middle Ages, the spirit of metaphysical speculation is alive and well-in computer science."

In the early days of science, not only was theory often given too much weight—so was observation. Before Charles Darwin and Charles Lyell provided a theoretical underpinning to biology and geology (respectively), these two sciences were largely descriptive. Botanists and zoologists would carefully describe the plants and animals they encountered and attempt to classify them by comparing their observable features with those of other plants and animals. Similarly, geologists would describe and categorize the geological formations found throughout the world. These botanists, zoologists, and geologists, however, were unable to make sense of their findings by placing them within their historical evolutionary context, and any attempt to theorize was generally discouraged. In an observation made by Darwin that Shermer elevated to a dictum, the great naturalist reflected in 1861: "About thirty years ago there was much talk that geologists ought only to observe and not theorize; and I well remember some one saying that at this rate a man might as well go into a gravel-pit and count the pebbles and describe the colours. How odd it is that anyone should not see that all observation must be for or against some view if it is to be of any service!"

Not only can Wolfram be accused of stressing theory over observation, but from a different perspective, of stressing observation over theory. To a large extent, Wolfram is an observationalist, but what he primarily observes is the artificial world on his computer screen, not the natural world. Wolfram carefully scrutinizes his virtual creations and categorizes them based on observed similarities. He only superficially observes complex natural systems to see if they resemble his computer creations. So, like pebble counting, Wolfram's new kind of science is primarily descriptive, not predictive. Descriptive science is a second-class citizen compared to predictive science. As the Nobel physicist Ernest Rutherford pointed out, "All science is either physics or stamp collecting." Stephen Wolfram is primarily a stamp collector, and Wolfram's hordes of fans and admirers should know that "philately will get you nowhere."

In fairness, however, Wolfram does not make observations for their own sake. He hopes that his observations will prove useful in understanding complex systems in nature. Nevertheless, this is backward from the way modern science is typically practiced. Scientists usually start with questions (problems), and then seek their answers (solutions). Thus, scientists would start with a complex pattern in nature and then try to explain it by reproducing the pattern with a computer program. Instead of this forward approach, Wolfram admits that he "looks at simple arbitrarily chosen programs, created without any specific task in mind."<sup>11</sup> He then checks to see which patterns, if any, generated by the programs resemble real-world phenomena. This process is like finding answers, then searching for their corresponding questions.

Wolfram cannot take the typical forward approach to science because there is no known practical method for finding CA-like rules that yield a desired pattern. Perhaps a forward approach could be taken if Wolfram started thinking like a physicist interested in natural systems instead of a mathematician interested in abstract systems. One could start with a detailed understanding of the physical system one is attempting to model. One could carefully study how the components making up a selected complex system interact, and then capture the essence of their interaction as a CA-type rule. Computers could then be used to implement the CA. If the computer-generated patterns closely resembled the pattern observed in nature, then one's model would be verified. This is not Wolfram's approach.

### Where is the Evidence?

So how much evidence does Wolfram offer for his "new kind of science?" As Carl Sagan often reminded us, extraordinary claims require extraordinary evidence; despite his extraordinary claims, Wolfram's evidence is quite meager. As many critics have pointed out, Wolfram does not offer any laboratory experiments or observations that support his grand claims. For instance, Jordan Ellenberg concludes, "For all its bulk, the book presents very little evidence to back up its claims." And Weinberg says that as far as he can tell, "there is not one real-world complex phenomenon that has been convincingly explained by Wolfram's computer experiments."

When scientists at the Caltech symposium challenged Wolfram to provide testable predictions of his new kind of science, Wolfram responded that the requirement of falsifiability does not apply to mathematics or computer science. He argued that his claims have the character of mathematics rather than physics. He used calculus as an analogy. Newton showed how calculus provides a new way of doing science. Calculus itself, however, is not tested to determine whether it is true or false. Its justification is that it works. The panel rightly rejoined that if this analogy is true, then Wolfram is just proposing a new kind of computational method, not a new kind of science. Indeed, as Feynman emphasized, "Physics is not mathematics, and mathematics is not physics." Unlike mathematicians, physicists must make testable predictions.

In NKS it is not until chapter 7 that Wolfram attempts to show the "striking similarities" between the patterns produced by CA and the patterns seen in nature. This similarity, Wolfram believes, "is not. . . any kind of coincidence, or trick of perception," but "reflects a deep correspondence between simple programs and systems in nature."<sup>12</sup> But how does Wolfram know that such similarities are not a coincidence? As previously mentioned, instead of selecting a natural phenomenon to model, Wolfram generates numerous patterns on the computer, then sees which, if any, resemble anything he can find in nature. With this backward methodology, is it really that surprising that similarities are found? As Krantz points out, "Just as the message of The Bible Code comes as no surprise. . . so it is really no great shock that virtually any visual image can be generated by some

cellular automaton."

Furthermore, with Wolfram's backward methodology, there is a danger of seeing patterns where none exist. As Shermer keeps reminding us, humans are pattern-seeking animals. Our impressive ability to see patterns, however, sometimes leads us astray. Stare long enough at thousands of tiny black-and-white squares on a computer screen, and we might imagine seeing all sorts of weird things. After all, we see constellations in the randomly distributed stars overhead. Could Wolfram be "seeing" patterns in his CA where none exist? According to Ridiculopathy.com, Wolfram's book has given rise to a new religion: Scientography. Fanatical followers of this religion believe "that the secrets of the universe, mind of God, and several hundred winning lottery numbers are hidden in the book's myriad patterns." And these followers "have claimed to see all sorts of bizarre items while exploring class 3 and 4 automata. These include images of Jesus, Elvis, crop circle designs, ...the words 'Paul (Erdos) is Dead,' and Jesus in an Elvis jumpsuit."

Where are Nature's Black-and-White Squares?

Wolfram needs to back up his theory that complexity in the real world is generated by simple programs by showing just how these programs correspond to actual mechanisms found in nature. Wolfram fails to do this, yet thinks he has already provided enough evidence that "a great many...phenomena can now for the first time successfully be explained."<sup>13</sup> "Just because Wolfram can cook up a cellular automaton that seems to produce the spot pattern on a leopard," remarks Krantz, "may we safely conclude that he understands the mechanism by which the spots are produced on the leopard, or why the spots are there, or what function (evolutionary or mating or camouflage or other) they perform?" The answer is clearly "no."

As another example, consider Wolfram's claim that a CA can produce patterns that resemble snowflakes. Some scientists counter, so what? Perhaps the real mechanism for snowflake production is much more complex than Wolfram's simple CA rules. Wolfram must show how his CA is instantiated in the physical world. In other words, he must explain why his CA resembles snowflakes. What feature of snowflakes represents cells and what underlying physical mechanisms within snowflakes represent the CA rules? Do the cells represent water molecules, and do the rules reflect the way water molecules physically interact with one another? Or rather, do the cells represent the individual hydrogen and oxygen atoms that make up the water molecules? Or perhaps the cells are made up of small chunks of ice. One cannot begin to empirically verify Wolfram's model of snowflake production until such issues have been settled.

Weinberg, in a review of Wolfram's book, assumes that water molecules represent the cells of Wolfram's CA. He then points out that Wolfram is faced with far more cells than his computer can handle. "Wolfram has found cellular automata in which each step corresponds to the gain or loss of water molecules on the circumference of a growing snowflake. After adding a few hundred molecules some of these automata produce patterns that do look like real snowflakes. The trouble is that real snowflakes don't contain a few hundred water molecules, but more than a thousand billion billion molecules. If Wolfram knows what pattern his cellular automaton would produce if it ran long enough to add that many water molecules, he does not say so."

Although it is natural to assume, as Weinberg does, that water molecules represent the cells of Wolfram's CA, Wolfram is very unclear on this issue. When discussing crystals, Wolfram seems to map the cells of his CA to atoms. At a "microscopic level," says Wolfram, "crystals consist of regular arrays of atoms laid out much like the cells in a cellular automaton."<sup>14</sup> When Wolfram discusses snowflakes, however, he seems to be talking of water molecules, not atoms. Wolfram states, "To a good approximation, all the molecules in a snowflake ultimately lie on a simple hexagonal grid."<sup>15</sup> Wolfram goes on to describe a few physical mechanisms of snowflake growth. He says, for instance, "in the actual process of snowflake growth, not every possible part of this grid ends up being filled with ice." This is because "whenever a piece of ice is added to the snowflake, there is some heat released which then tends to inhibit the addition of further pieces of ice nearby." Note that Wolfram now seems to be saying that it is pieces of ice that are represented by the cells of CA, not individual water molecules or their atoms.

So in Wolfram's CA model of snowflakes, what do cells consist of? Are cells hydrogen and oxygen atoms, water molecules, or pieces of ice? And whatever the answer, how does the physical behavior of these entities resemble the CA rules? Amazingly, Wolfram believes that he does not need to provide answers to these questions. "One might perhaps think," asserts Wolfram, "that in the end one could always tell whether a model was correct by explicitly looking at sufficiently low-level underlying elements in a system and comparing them with elements in the model. But one must realize that a model is only ever supposed to provide an abstract representation of a system-and there is nothing to say that the various elements in this representation need have any direct correspondence with the elements of the system itself."<sup>16</sup> Shortly thereafter in his book, Wolfram says that "countless times I have been asked how models based on simple programs can possibly be correct, since even though they may successfully reproduce the behavior of some system, one can plainly see that the system itself does not, for example, actually consist of discrete cells that, say, follow the rules of a cellular automaton." But for Wolfram, "There is no reason that the model should actually operate like the system itself."<sup>17</sup> So when it comes to the CA rules for generating snowflakes, Wolfram states "there is no need for the rule to correspond in any way to the detailed dynamics of water molecules."<sup>18</sup>

Wolfram has been asked "countless times" how his models can be correct when they do not operate like the systems they supposedly model. He has been asked countless times because his position seems so blatantly wrong. A model is not a "black box" whose inner workings are divorced from reality. As Feynman stated, "in physics you have to have an understanding of the connection of words with the real world. It is necessary at the end to translate what you have figured out into English, into the world, into the blocks of copper and glass that you are going to do the experiments with. Only in that way can you find out whether the consequences are true."<sup>19</sup> Wolfram, however, fails to translate his cells and rules to features of the real world.

Wolfram himself seems to forget his own position when, for example, he discusses the second law of thermodynamics: "My approach in investigating issues like the Second Law is in effect to use simple programs as metaphors for physical systems. But can such programs in fact be more than that? And for example, is it conceivable that at some level physical systems actually operate directly according to the rules of a simple program?"<sup>20</sup> Is Wolfram now admitting that unless his CA models operate like the systems they are modeling, these models are merely metaphors? Is the foundation for Wolfram's new kind of science merely a metaphor? Consider what Wolfram says about the complex patterns seen on many mollusk shells: "Modern molecular biology should be able to isolate the specific programs responsible. . .for the patterns on mollusk shells, and see explicitly how long they are. But there are already indications that these programs are quite short." Wolfram then states that the similarity between patterns on mollusk shells and his CA is "no coincidence." "A mollusk cell, like a one-dimensional cellular automaton, in effect grows one line at a time, with new shell material being produced by a lip of soft tissue at the edge of the animal inside the shell. Quite how the pigment on the shell is laid down is not completely clear. There are undoubtedly elements in the soft tissue that at any point either will or will not secrete pigment. And presumably these elements have certain interactions with each other. And

given this, the simplest hypothesis in a sense is that the new state of the element is determined from the previous state of its neighbors-just as in one-dimensional cellular automaton."

If, as Wolfram claims, the validity of his CA models do not in any way depend on the actual workings of the systems they model, then why is Wolfram making the effort to describe how the patterns on mollusk shells arise? Indeed, what makes Wolfram's explanation of the patterns on mollusk shells especially persuasive is the natural way his CA can be mapped to the underlying physical mechanisms that generate the patterns on mollusk shells. But this need for a mapping also points to the greatest weakness of Wolfram's book. Science is an empirical endeavor. Wolfram's numerous computer experiments with simple CA-like programs must eventually be anchored to reality. Until it is shown in convincing detail how his CA map to physical systems, his book amounts to little more than interesting speculation.

So how does Wolfram justify his seemingly unreasonable claim that CA models do not need to operate like the systems they model? Wolfram's justification is based on the observation that mathematical models also do not need to operate like the systems they model. "A traditional mathematical model might say that the motion of a planet is governed by a set of differential equations," Wolfram explains. "But one does not imagine that this means that the planet itself contains a device that explicitly solves such equations. Rather, the idea is that the equations provide some kind of abstract representation for the physical effects that actually determine the motion of the planet."<sup>21</sup> Is this analogy between models based on programs and those based on equations valid? There are at least three reasons the analogy may not be valid.

1. CA programs are procedural, so one needs to identify their corresponding physical procedures. These programs describe how, by repeatedly applying a set of simple steps, one arrives at a particular result. What could be more important than to know how those steps are implemented in a real world? Wolfram provides a recipe without identifying the ingredients. Without listing those ingredients, we may derive a nice abstraction, but we will never get to eat our sacher torte.

2. Models used in science typically incorporate fundamental equations that can be tested independently of the model. For instance, a model of a swinging pendulum incorporates the well-established, and independently verifiable, principle of inertia. In addition, because of their generality, equations that are employed in one model can often be employed in many other models dealing with similar phenomena. In Wolfram's new science, however, models incorporate rules that cannot be independently verified. These rules are just arbitrary procedures for determining the color of a cell. For this reason, the only way that Wolfram can anchor his rules to reality is by showing how nature implements them. And this is something he is far from adequately accomplishing.

3. Models should operate like the systems they model. If they do not, the model is often replaced with a more realistic one. For instance, when Claudius Ptolemy employed a complex system of epicycles (a circle whose center is carried around the circumference of another circle) upon epicycles to calculate the motion of the planets, not everyone was satisfied with the model. As useful as epicycles were as a model-and many believed they were-they did not correspond to reality. It was reasonable to go further and determine how planets really move. Johannes Kepler eventually discovered that planets orbit the Sun in ellipses, with the Sun at one foci of each ellipse.

Of course, not all models are as concrete as the ones describing planetary motion. Consider the abstract models governing the subatomic world. When entering the strange subatomic realm ruled by quantum mechanics, our common sense notions and intuitions break down. As a result, our models of subatomic particles are very abstract and lack concrete mechanisms. For instance, physicists claim subatomic particles such as electrons have spin, but this spin is very different from that of spinning planets and tops. An electron appears to be rapidly spinning because it possesses a tiny magnetic field and angular momentum. However, unlike a spinning top, the spin of an electron never changes, has only two possible orientations, and possesses a half spin. The necessity of using such abstract notions in the subatomic realm, however, should not provide Wolfram with an excuse not to address the underlying mechanisms of his rule-based models.

#### The Power of Equations

Computer programs such as those used by Wolfram lack the explanatory and predictive power of the equations used in traditional science. Wolfram states that an equation "relies on being able to shortcut the computational work that the system itself performs."<sup>22</sup> So from Wolfram's point of view, for example, a planet's motion around the Sun, like everything else in the universe, can be viewed as a computation. Suppose we want to determine where Jupiter will be at 11:00 pm next Tuesday. Instead of just waiting until that time arrives to see the results of nature's computation, we can use equations as a "shortcut" for getting the answer in advance. Wolfram argues, however, that many complex systems are computationally irreducible, which means that shortcuts, and hence the equations that rely on them, are not possible. However, regardless of how many actual systems are computationally irreducible, equations do far more than provide shortcuts. Equations may capture universal principles, function as organized reasoning, lead to new discoveries, and explain other equations.

#### Equations Capture Universal Principles

The real explanatory power of equations, such as Newton's law of gravitation, derives from their universality. According to the legend, after being hit on the head by a falling apple, Newton realized that the same force of gravity that pulls objects such as apples toward the Earth, also pulls the planets toward the Sun. In fact, gravity acts between any two objects, whether they are galaxies, stars, planets, mountains, people, or golf balls, based on the following simple formula:

##### IMAGE FORMULA

This law of gravitation states that two bodies exert a force ( $F$ ) upon each other that varies inversely as the square of the distance ( $r$ ) between them, and varies directly as the product of their masses ( $m$  and  $m'$ ). ( $G$  is the gravitational constant.)

So how universal are the simple programs that Wolfram offers as his new kind of science? Whereas Newton's law of gravitation, with some limitations, is universally applicable to all physical objects in the universe, a particular CA is not universally applicable. The CA Wolfram uses to produce patterns resembling snowflakes, for instance, is different from the CA he uses to describe the patterns on the shells of mollusks. Even if, as Wolfram suspects, both CA are universal computers, it may be totally impractical to identify the required input (initial row of cells) that enables one CA to simulate the other. Furthermore, such simulation may require far too much computing power ever to be carried out in practice. But even forgetting such practical issues, Weinberg calls Wolfram's theory "free-floating," like thermodynamics, chaos theory, and the theory of broken symmetry. Such free-floating theories, Weinberg argues, are not as fundamental as equations capturing the universal laws of nature because, unlike universal laws, free-floating theories "may or may not apply to a given system. . . [T]o justify applying one of these theories in a given

context," continues Weinberg, "you have to be able to deduce the axioms of the theory in that context from the really fundamental laws of nature."<sup>23</sup>

#### Equations Function as Organized Reasoning

Feynman pointed out that mathematics is not simply a language, but "organized reasoning."<sup>24</sup> It "is a way of going from one set of statements to another."<sup>25</sup> Indeed, equations such as Newton's law of gravitation can be used to connect seeming unrelated facts, thereby providing a deeper understanding of the universe. Newton, for instance, demonstrated that Kepler's law-that planets sweep equal areas in their orbital ellipse in equal times-is a direct consequence of the idea that changes in velocity are directed towards the Sun. Furthermore, Newton employed his law of gravitation to explain why, as Galileo observed, objects that slip from our fingers drop 16 feet in their first second of falling, why planets orbit the Sun in an ellipse, why we have two ocean tides each day, and why the Earth is basically spherical, but with a slight bulge at its equator. Before Newton came along, nobody could imagine how such varied phenomenon could be explained by the same laws.

In contrast to equations, the rules of CA do not reflect organized reasoning, but are arbitrary procedures, to be carried out over and over again.

#### Equations Lead to New Discoveries

Equations can lead to new discoveries. For example, after the English physicist and chemist Henry Cavendish performed an experiment to calculate the gravitational constant G, Newton's law of gravitation was used to accurately calculate the mass of the Earth and other heavenly bodies. New discoveries were also made when Newton's law of gravitation seemed to fail, but was later vindicated. For example, an observed discrepancy in the orbit of the moons around Jupiter was finally explained and led to the determination of the speed of light. Similarly, because of an unexpected deviation in the orbital path of Uranus, Neptune was discovered. And recently, anomalies in the motions of galaxies led to the discovery of a mysterious "dark matter" that permeates the universe.

Wolfram, despite his grandiose claims, fails to provide any surprising new discoveries that have been empirically verified.

#### Equations Explain Other Equations

Nature's laws can be explained by being derived from more general laws that are more accurate over a wide range of phenomena. For instance, Einstein's relativistic law of gravitation explains Newton's law of gravitation, which in turn, explains why planets follow Kepler's laws of planetary motion. Each time a more general law is discovered, it answers many of the old questions but raises new ones. Kepler's three laws of planetary motion, for instance, captured how planets orbit the Sun, but these laws could not explain what propels the planets. Lacking a scientific explanation, some religious thinkers invoked the "God in the gaps" argument that remains so popular today, especially among Creationists. These thinkers claimed that because a naturalistic explanation is lacking, a supernatural explanation should be invoked. In this case, their explanation was that angels, beating their wings with great vigor, push the planets along their elliptical paths.

Newton finally provided a scientific answer to the question of what propels the planets. Using Galileo's principle of inertia, he showed that no angels were needed to push the planets along, just the force of gravity pulling the planets towards the Sun. But Newton could not explain how the Sun, which is about 93 million miles from Earth, can instruct the Earth how to move. How can gravity act over such large distances? And what seemed particularly mysterious is how gravity affects all objects in the same way. The strength of gravity depends on an object's mass, but gravity could not care less whether the object is made of metal, wood, plastic, or prune pudding, or whether the object is baked, steamed, or stir-fried. Albert Einstein provided answers to such vexing questions, at least to some extent. Einstein avoided the need to explain how gravity can act at a distance and how it is indifferent to an object's composition by showing that gravity is not a force.<sup>26</sup> Instead, said Einstein, gravity is a manifestation of the warpage of space-time. Massive objects, such as our Sun, warp the space-time around them. The planets respond locally to the curvature of space-time. (Think of the simple analogy of a bowling ball stretching a sheet of rubber and little marbles rolling around the curvature of the warped rubber sheet.) Thus, there is no mysterious action at a distance. And the reason gravity acts the same on all objects, regardless of the object's composition, is that gravity is a property of space-time itself.<sup>27</sup>

So nature's laws can be explained by being derived from more general laws. As a result, questions are answered that thereby give us a deeper understanding of nature. It is hard to see how Wolfram's simple programs can provide such a hierarchy of understanding.

#### What is Complexity?

When it comes to complexity Wolfram sees the world in black and white, like the cells on his computer screen. Systems are either simple or complex, with nothing in between. Furthermore, Wolfram sets the threshold for being complex "extremely low," although he does not define this threshold. Thus, as he explained to an incredulous New York Times interviewer, the behavior of a CA rule, human intelligence, and a bucket of rusting nails are equally complex, and all are universal computers. Instead of seeing this absurd conclusion as a repudiation of his notion of complexity, Wolfram treats it as a profound insight. Perhaps parents should establish a college fund for their bucket of nails as well as for their kids. But even if a bucket of nails is a universal computer, how could we program it (or provide the proper input) to make it model intelligence? As Goertzel points out, there is a "nasty little efficiency" issue that is the "biggest thorn in the side of the theory of universal computation." In principle, any universal computer can simulate any other computer by running an appropriate program. For instance, because rule 110 is universal, it can, in principle, model the human brain. However, running this program could require more memory elements than there are atoms in the known universe and more processing time than the age of the universe. Decoding the program's output could be equally impossible.

#### Reasons for Seeking Simplicity

Wolfram implies that simple systems, such as swinging pendulums and the orbit of the moon around the Earth, although easy to study, are uninteresting. He believes that the really interesting systems are the complex ones that scientists fail to tackle, intimidated by their difficulty. Scientists, however, deliberately choose to study simple systems, not because they necessarily find these systems interesting in themselves, but because they are seeking universal laws. Seeking the laws of nature requires one to learn how to strip away complexity and view a phenomenon in its bare essence. For example, by studying how pendulums swing

and how balls roll down inclined ramps, Galileo discovered the principle of inertia. According to this principle, an object moving in a straight path and at a certain speed will continue to do so unless something acts on it. Of course, because of influences such as friction and air resistance experienced on Earth, rolling balls and swinging pendulums eventually come to rest. These systems, however, are simple enough to have allowed Galileo to infer what would happen when complicating factors, such as friction, were eliminated. In complex systems, too much is going on to easily discern any underlying laws. Thus, it is very unlikely that Galileo would have made his important discovery of the principle of inertia had he investigated complex systems, such as multiple beams that are hinged together to produce chaotic swinging motions, or the motion of millions of grains of sand as they cascade down a sand dune.

### Can Equations Explain the Complex?

If our solar system consisted of just the Earth and Sun, then Newton's law of gravitation could predict the Earth's orbit with great precision. Our actual solar system, however, is more complex. Not only does the Sun's gravity attract all the planets, but also the gravity of each planet attracts the others. Accurately calculating mutual attraction of the planets is quite difficult. No simple, standard mathematical equation has been found to calculate the actual motions of three or more gravitationally interacting bodies (the "three-body problem").<sup>28</sup> Wolfram suspects no such equation will ever be found because the three-body problem is computationally irreducible. Nevertheless, techniques involving, for instance, infinite series, can yield very good approximations. Furthermore, even though simple equations cannot be used to calculate the actual motions of multiple interacting bodies, they can nevertheless describe their motions. As Weinberg points out, "Even before physicists and astronomers learned in the nineteenth century how to take account of mutual attraction of the planets in accurate calculations of their motions, they could be reasonably sure that the planets move the way they do because they are governed by Newton's laws of motion and gravitation."<sup>29</sup> Thus, it is possible to understand the fundamental principles governing a complex system, even though its actual behavior cannot be accurately calculated. Wolfram's insistence that complex systems can only be understood by modeling their actual behavior seems too extreme, and may not even yield as deep an understanding as provided by the basic principles governing the system.<sup>30</sup>

### When is a System Computationally Irreducible?

How can we know whether a system that looks complex is computationally irreducible? Wolfram fails to answer this question, yet seems sure that the complex output of CA such as rule 110 is computationally irreducible. Currently, no shortcut is known for determining the color of a specified square on a specified row, but how can we know that such a shortcut will never be found?

Consider the digit sequence of pi, which Wolfram agrees, "seems for practical purposes completely random." Until recently, it was assumed that the rules that generate this digit sequence are computationally irreducible—that the only way for determining, say, the 10,000th digit of pi, is to calculate all its preceding 9,999 digits. But mathematicians were stunned by a recent discovery by David H. Bailey of NASA Ames Research, Peter B. Borwein of Simon Fraser University, and Simon M. Plouffe, now at the University of Quebec. These researchers, with major help from a computer, found a novel formula "to calculate any digit of pi... without having to know any of the preceding digits, a feat assumed for millennia to be impossible."<sup>31</sup> "No one had previously even conjectured that such a digit-extraction algorithm for pi was possible," says Steven Finch of MathSoft, Inc. If a totally unexpected shortcut was found for calculating a specific digit of pi, how can we rule out the possibility that some future genius (or computer) will discover a shortcut for determining the outcome of Wolfram's supposedly computationally irreducible CA?

### Biological Complexity

Perhaps the strongest case Wolfram makes for his new kind of science is when he explores biological complexity. As shown in Figure 3, it is hard to compare the pigmentation patterns found on mollusk shells with those generated by his CA without being struck by their uncanny similarity.

The patterns on mollusk shells, Wolfram argues, are not the product of Darwinian natural selection; the patterns were not selected because they help mollusks avoid predators or attract mates or prey. Simple CA-like programs selected at random, Wolfram believes, generate the patterns on mollusks. (Wolfram suggests that these programs "are in essence just reflections of completely random changes in underlying genetic programs."<sup>32</sup> Unlike CA programs, however, genetic programs are very fussy as to what rules encoded in DNA are acceptable.) Typically, all possible patterns available through such simple programs will be expressed in nature. Natural selection, Wolfram believes, will only weed out a pattern in the unlikely event that it turns out to be disastrous for the organism. But when it comes to survival and reproductive success, why—as Wolfram believes—should all patterns typically be equal? Perhaps some patterns provide better camouflage than other patterns. Wolfram counters that the patterns on many species of mollusks are hidden behind an opaque skin (periostracum) and not exposed until after the mollusk dies. These mollusks, however, may have evolved from species where the patterns were exposed during their life. Perhaps the advantage of possessing patterns was more than compensated by the advantage of having a protective skin. These hidden patterns might just be part of the mollusk's genetic legacy, like the nonfunctional eyes on blind cave salamanders.

#### IMAGE ILLUSTRATION

Figures 3-a CA-like pattern on a mollusk shell.

Wolfram believes his pronouncement that mollusk patterns do not confer adaptive advantage is a radical departure from the established scientific wisdom that "essentially every feature of every organism can be explained on the basis of it somehow maximizing the fitness of the organism."<sup>33</sup> Wolfram seems oblivious to the fact that many biologists would agree that superficial features such as pigmentation patterns are not adaptive traits picked out by natural selection. Not every feature of an animal has survival or reproductive value. There may be features of an animal that are neutral when it comes to helping or hindering the chances of surviving and reproducing. The ongoing debate in biology between major theoreticians such as Richard Dawkins (a selectionist) and the late Stephen Jay Gould (a neutralist) is over how prevalent such nonadaptive features are in the biological world. Gould, for instance, states that natural selection "cannot suffice as a full explanation for many aspects of evolution; for other types and styles of causes become relevant, or even prevalent..." As Hayes notes, Wolfram "writes as if he were unaware that a debate between neutralists and selectionists had ever entered biology."

To further bolster his case that patterns on mollusk shells were created by simple programs, Wolfram points out that, like one-dimensional CA, these patterns are built up one row at a time. (Most patterns on animals develop simultaneously all over the surface.) But even though patterns on mollusk shells are built up a row at a time, Wolfram has a lot of questions to answer. How do the cells and simple rules of CA relate to the pigments, which are made by enzymes, which are made by ribosomes, which are made of a wide assortment of large and complex organic molecules? Do pigment-secreting biological cells communicate with

neighboring cells through the exchange of chemical signals that follow the rules of Wolfram's CA? As previously pointed out in this article, contrary to Wolfram's view, such issues need to be addressed in detail in order to anchor his models to reality.

### Functional Complexity versus Structural Complexity

Wolfram believes "the most dramatic examples of complexity in biology. . . often involve patterns or structures that look remarkably like those in physics."<sup>34</sup> Wolfram, however, misses the essential difference between living and nonliving things. As Shark Stewart asserts in the University of Chicago Magazine, unlike the complexity found in nonliving systems, "Biological systems are very complicated and very complex, but they have clear functionalities. For organisms things have to be done and done right." Wolfram is misled because he focuses on trivial biological features such as pigmentation patterns and branching patterns that are easy to visually perceive. Indeed, Wolfram's entire book is focused on visual images. But whereas it is easy to compare CA-generated patterns to the designs seen on mollusk shells, how could one compare these CA-generated patterns to the metabolism of mollusks? What would one look for in the pattern of squares that represents metabolism? Yet it is functional complexity such as metabolism, the Krebs cycle, or photosynthesis that are of prime interest to biologists. At the Caltech symposium, Chris Adami, director of Caltech's Digital Life Laboratory, noted that Wolfram tries to explain complex patterns based on our perception and our inability to perceive the simple rules that can generate such patterns. In contrast, biologists are concerned with functional complexity that arises as organisms adapt to various environments, thereby increasing their chance of survival and reproduction. Adami finds it inconceivable that the functional complexity of living organisms in which the digestive, circulatory, lymphatic, immune, and nervous systems work together for the good of the organism is due to a simple underlying rule.<sup>35</sup>

Consider the functional complexity of the human eye. The human eye presents our brain with colorful, focused images of the external world. It contains many parts that must all function together in a coordinated manner. Wolfram tries to relate CA to the processing that underlies our perception of patterns and textures. He views the retina as an array of light-sensitive squares and the visual cortex as possessing a similar array. Wolfram, however, does not explain the eye as a complete functionally complex system.

According to Darwinian natural selection, the eye gradually emerged through the successive accumulation of numerous improvements, each of which was simple enough to have emerged by chance. Through the process of natural selection, each improvement, however slight, is preserved, and forms the basis for the next improvement, which forms the basis for the next improvement, and so on, for countless generations. Natural selection is not, as Wolfram thinks, "being asked to predict what changes would need to be made in an underlying program in order to produce or enhance a certain form of overall behavior."<sup>36</sup> Furthermore, it is hard to understand what Wolfram means when he says, "in natural selection an iterative random search process is used."<sup>37</sup> Nature doesn't try out all solutions to find the optimal one. Because evolution tinkers with structures and genes already at hand, optimal solutions are rarely found. What are found are jerry-rigged modifications of previously existing structures.

The plausible stages of our eye's development can be found among today's living animals. On the rudimentary side, for instance, one-celled marine organisms such as the Euglena have a simple eyespot consisting of a flat patch of light-sensitive cells. Although the eyespot can only vaguely determine the presence of a light source, it provides the organism with an obvious advantage.

As evolution progressed, the flat eyespots of our distant ancestors became more and more recessed, eventually forming deep cups, as seen in some of today's shellfish. These recessed eyespots provide greater ability to determine the direction of a light source. Eventually, the opening to the recessed cup became small enough that it acted as a pinhole camera capable of focusing an image. Pinhole camera eyes can be seen in today's nautilus. Even without the ability to focus a clear image, pinhole eyes allow animals such as the nautilus to detect the motion of their prey or the direction of a predator. In time, the pinhole opening got covered by a translucent material, which acted as a crude lens to collect and concentrate light. Scallops, for instance, have eyespots, each with a crude lens. As the lens material evolved, it thickened and became clearer and less distorting, thus producing the sharp, bright images enjoyed by most of today's vertebrates, including humans.

So how does Wolfram's new kind of science explain a functionally complex system such as a human eye? Wolfram suspects that "in the end natural selection can only operate in a meaningful way on systems or parts of systems whose behavior is in some sense quite simple."<sup>38</sup> Although Wolfram never demarcates the simple from the complex, it certainly seems that the eye must be categorized as complex. So if natural selection does not explain the emergence of the eye, a simple program must explain it. But how can a simple CA-like program capture the functional complexity of a human eye? Wolfram's answer is that "important new features of organisms. . . come from programs selected purely at random."<sup>39</sup> Does Wolfram claim, then, that the eye is the result of a simple program that arose by chance? Did this simple program create the human eye in one fell swoop without the benefit of natural selection? Answering these questions in the affirmative seems extremely farfetched. Out of the seemingly countless number of possible simple programs, how did one appear that produces something as fantastically useful as the human eye? The odds of this happening seem infinitesimally small (as creationists are fond of pointing out). Furthermore, eyes have independently evolved dozens of times among different sorts of animals. A human eye and an octopus eye, for instance, did not evolve from the eye of some common ancestor; each arose independently of the other. By Wolfram's reasoning, each distinct kind of eye found in nature must have been generated by slightly different programs. So what are the odds of all the variations of eye-generating programs randomly appearing? Wolfram has much explaining to do. He claims that his new kind of science leaves no room for God, but then who or what selected all the eye-generating programs from all the countless other programs that failed to generate anything even remotely as useful as an eye?

Wolfram strongly suspects that "the reason certain structures appear repeatedly is just that they are somehow common among programs of certain kinds. . . ." <sup>40</sup> This implies that there are many simple programs that generate various types of eyes, and these simple programs are so common that we should not be surprised that eyes arise over and over again. If this is Wolfram's position, it certainly is extraordinary.

Note that an important feature of functional complexity found in biological systems is its robustness. Biological systems are incredibly complex, yet in order for the organism to survive, these systems have to be very robust. If they undergo chaotic transitions, as do many CA, the organism dies. Furthermore, at the Caltech symposium, John Preskill challenged Wolfram by pointing out that CA are very fragile. "Mutations" to CA, such as a random change of color of a few squares, or even worse, a change to one of its rules, is often enough to turn its elaborate structure into rubble. In contrast, biological systems must be stable even when mutations and other errors are introduced from interactions with the external environment. Thus, most CA

cannot simulate complex living things. Fault-tolerant (error correcting) CA are extremely complex and would not be the kind of simple programs Wolfram believes govern the universe. Furthermore, as Gray points out, "it is not clear that nature could easily find a mechanism that behaves like a fault-tolerant UCA [universal cellular automata] without some 'guiding hand' like natural selection." Gray continues, "Until someone finds a simple fault-tolerant UCA, the main theme of NKS remains wishful speculation."

Wishful speculation. Is that all Wolfram has produced? That is certainly the opinion of many experts and scientists in the many and varied fields tackled by Wolfram. "Time will tell" seems to be the most generous assessment made by those of a skeptical bent. As with all claims, extraordinary or not, the burden of proof lies with the claimant. We shall see how Wolfram responds to his skeptics. His response will be a testimony to his scientific integrity, as well as to the veracity of his theory.

SIDEBAR

"Wolfram's flawless credentials, staggering intelligence, and depth of knowledge strongly suggest that he is no crank. . .yet Wolfram displays many attributes associated with being a pseudoscientist."

SIDEBAR

"Wolfram's book, A New Kind Of Science lacks traditional references to scientific papers and books on related topics. It contains no bibliography."

SIDEBAR

"Although Wolfram does not claim natural selection is totally without merit, he does claim it is insufficient to fully explain the complexity found in the biological world."

SIDEBAR

"Although Wolfram's work is not pseudoscience, it does not follow that it is science. It is possible that Wolfram's work is neither science nor pseudoscience, but something more akin to mathematics, game theory, or philosophy."

SIDEBAR

"Is Wolfram now admitting that unless his CA models operate like the systems they are modeling, these models are merely metaphors? Is the foundation for Wolfram's new kind of science merely a metaphor?"

SIDEBAR

"Computer programs such as those used by Wolfram lack the explanatory and predictive power of the equations used in traditional science."

SIDEBAR

"Wolfram, despite his grandiose claims, fails to provide any surprising new discoveries that have been empirically verified."

SIDEBAR

"Wolfram implies that simple systems, such as swinging pendulums and the orbit of the moon around the Earth, although easy to study, are uninteresting. He believes that the really interesting systems are the complex ones that scientists fail to tackle, intimidated by their difficulty."

REFERENCE

References

1 Wolfram, S. 2002. A New Kind of Science. Wolfram Media, Inc., 2.

2 If one views each row as the next state of the previous row, then the color of a cell depends on its previous color (shown in the cell directly above it) and the color of its previous neighbors to the left and right.

3 There are 256 elementary one-dimensional CA with two colors and nearest-neighbor rules. The number of possibilities explode when adding dimensions, colors, or extending the nearest-neighbor rules. For instance, just by adding a third color, the number of possibilities becomes 7, 625, 597, 484, 987.

4 Wolfram, 2002, 545.

5 Ibid., 41.

6 In about 1985, Wolfram conjectured that rule 110 is a universal computer. In the late 1990s, this conjecture was reportedly proven by Matthew Cook, a former employee of Wolfram Research, Inc. If this proof holds, then rule 110 becomes the simplest universal computer discovered.

7 James Horgan told me this story when I met him at a Caltech lecture he gave for the Skeptics.

8 Wolfram, 2002, 1.

9 Ibid., 50, 876-877.

10 Feynman, R. 1965. The Character of Physical Law. Cambridge, MA: M.I.T. Press, 58.

11 Wolfram, 2002, 23.

12 Ibid., 298.

13 Ibid., 298.

14 Ibid., 369.

15 Ibid., 370.

16 Ibid., 365.

17 Ibid., 366.

18 Ibid., 366.

19 Feynman, 1965, 55-56.

20 Wolfram, 2002, 434.

21 Ibid., 365-366.

22 Ibid., 6.

23 Weinberg, S. October 24, 2002. "Is the Universe a Computer?" The New York Review of Books.

24 Feynman, 1965, 41.

25 Ibid., 45.

26 Although Einstein's model of gravity is mathematically equivalent to systems that are not based on curved space-time, as Feynman pointed out, these alternative systems are not psychologically equivalent. These alternative systems lead to a different line of further questions and research.

27 By analogy, imagine looking down from a high building at a trampoline that has a heavy cannon ball resting at its center. Suppose some kids throw a few tennis balls on the trampoline that then spiral inwards towards the cannon ball resting at its center. From high up, you might not see that the trampoline is indented, and therefore might assume that the cannon ball is pulling the tennis balls toward it. When getting closer, however, you realize that that cannon ball is not exerting some mysterious force, but that the tennis balls are just reacting to the curvature of the trampoline below them and following the "path of least resistance" (geodesic). In a similar manner, Einstein showed that massive objects, such as our Sun, warp space-time as the cannon ball warps a trampoline. The planets respond locally to the curvature of space-time like the tennis balls respond locally to the indented trampoline. (Do not take this analogy too far, however. The curvature of space-time is in four dimensions, not in the two dimensions of a trampoline's surface. And unlike the trampoline that is deflected in a higher third dimension, four-dimensional space-time is not deflected in a higher dimension.) Thus, there is no mysterious action at a distance. In 1919, the astronomer Sir Arthur Eddington tested Einstein's claim that the Sun actually bends space-time during a total solar eclipse by observing that light from a distant star that passes close to the Sun is deflected just as Einstein predicted. (To see a faint star near the bright Sun, Eddington traveled to Brazil to witness a solar eclipse.)

28 In more technical terms, equations cannot be solved in "closed form solutions."

29 Weinberg, S. 1992. Dreams of a Final Theory, Vintage Books, 9-10.

30 To understand a complex phenomenon, one does not have to account for its behavior in all its gory details; in his models Wolfram admits this: "Any model is ultimately an idealization in which only certain aspects of a system are captured, and others are ignored." Wolfram states that it is not his purpose "to explain every detail" of all the various kinds of systems he discusses. Instead, Wolfram wants "to identify the basic mechanisms that are responsible for the most obvious features of the behavior of each kind of system" (page 363). But is this not what scientists already do? Globular clusters, for instance, consisting of thousands of closely packed stars, are well understood. This does not mean we can precisely calculate how all the stars in a globular cluster actually move. The motion of all the stars is extremely complex, but we can feel reasonably assured that the basic underlying mechanism is the same as the one that explains how the Moon orbits the Earth.

31 Gibbs, W. W. May 2003. Scientific American, 23-24.

32 Wolfram, 2002, 396.

33 Ibid., 387.

34 Ibid., 397.

35 Adami also took exception to Wolfram's claim that evolution is unimportant. Adami pointed out that Darwinian evolution in general, and natural selection in particular, are of fundamental importance to biologists; without Darwinian evolution, biology does not make sense.

36 Wolfram, 2002, 393.

37 Ibid., 394.

38 Ibid., 392.

39 Ibid., 399.

40 Ibid., 397.

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