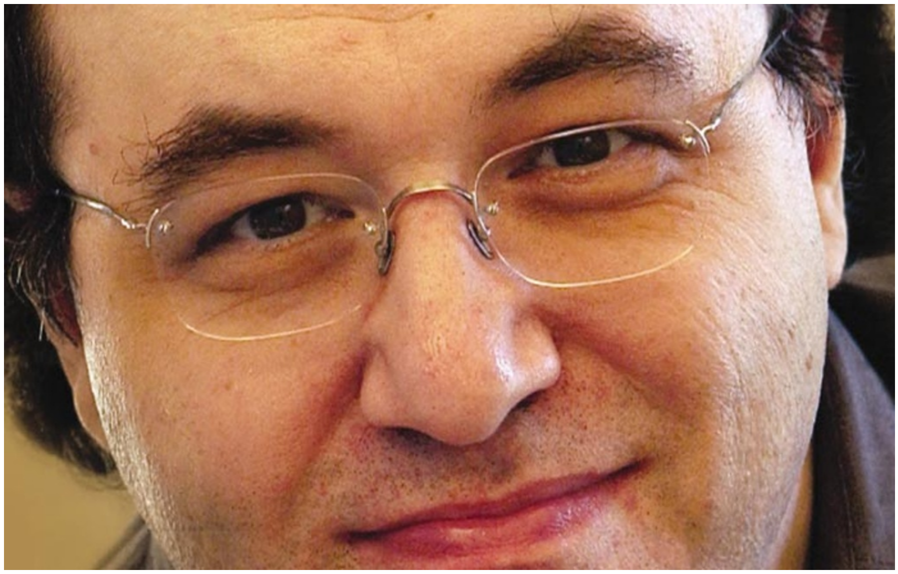
What kind of science is this?

Mathematical prodigy Stephen Wolfram has laboured for a decade on what he claims is a revolutionary book. Jim Giles meets a supremely confident scientific loner, but finds expert opinion on the work's merits divided.

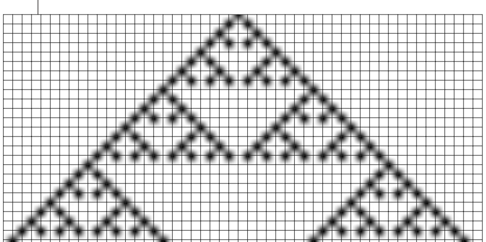


D. REISS/WOLFRAM RESEARCH

To all intents and purposes, Stephen Wolfram dropped out of the research community more than a decade ago. Since 1988, he has neither published a scientific paper nor attended a conference. But the British-born mathematician has not been idle. Working long into the night, gazing into the screen of his computer at his Chicago home, Wolfram claims to have sown the seeds of a scientific revolution.

The fruits of this solitary labour are revealed this week in the mammoth tome *A New Kind of Science* (Wolfram Media, Champaign, Illinois, 2002). It is a call for researchers to turn away from calculus and other conventional mathematical tools and to embrace instead simple 'rules' that can be applied to generate patterns of astounding variety and complexity. Hidden within these patterns, Wolfram asserts, are the keys to understanding a multitude of biological and physical phenomena from the shapes of leaves to the structure of space-time itself. He suggests that his work will change almost every branch of the natural sciences, and even social sciences and the arts. "All the media are going to follow this — and in a big way," he predicts.

Coming from most authors, such grand claims would instantly be dismissed as empty hype. But Wolfram's track record will ensure that many scientists will reserve their judgement. A bona fide prodigy, Wolfram published his first paper on theoretical high-energy physics aged 15, and later breezed through a PhD in a year. Before turning 30, he had helped to launch the discipline of complex-systems research and had founded a mathematical software company that has since made him — at the still relatively tender age of 42 — a very wealthy man.



Starting with a single black square, a simple cellular automaton can generate nested triangles.

The book's title typifies a brash approach that many characterize as arrogance. "I was successful in science early in life," Wolfram says matter-of-factly, over a restaurant meal in Cambridge, Massachusetts. "It leads to a certain degree of self-confidence." But do the book's 1,200-odd pages really detail a new way of doing science? Or has Wolfram's supreme self-belief, unfettered by the need to convince the wider research community that his ideas are valid, fooled him into mistaking an interesting but ultimately limited set of results for something far more significant? As his book hits the shelves, the jury is deliberating.

> I trust my judgement. I wanted to build a big intellectual structure and explain it in a coherent way.
>
> **Stephen Wolfram**

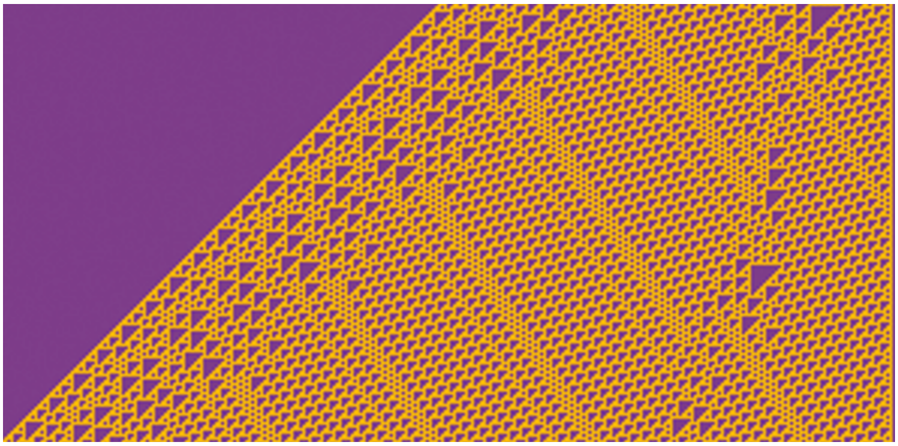
Precocious talent

The ideas in *A New Kind of Science* have been brewing in Wolfram's mind since the early 1980s. After ducking out of an undergraduate degree at the University of Oxford because he found it insufficiently challenging, Wolfram was in 1978 lured to the California Institute of Technology (Caltech) in Pasadena by Nobel physics prizewinner Murray Gell-Mann. The following year, he gained his PhD by submitting a bundled collection of his papers on high-energy physics and cosmology, and then joined the Caltech faculty in 1980, before moving to the Institute for Advanced Study in Princeton, New Jersey, in 1983.

"Various areas in science were stuck," Wolfram recalls. Traditional mathematical methods were, for example, struggling to show how galaxies could form from the featureless gas of the early Universe. Even mundane processes such as the growth of snowflakes were proving difficult to simulate.

Wolfram wanted to model such phenomena, and turned to simple systems known as cellular automata. The simplest 'one-dimensional' cellular automata consist of a line of squares, which can be either black or white. Each time the system is updated, a new line is created following a simple rule, and is often displayed underneath the previous line so that the evolution of the system can be tracked. One rule, for example, says that a square in the new line should only be black if one or the other, but not both, of its predecessor's neighbours were black. Starting with a single black square in the first row of squares, this rule produces a pattern of nested triangles (see left).

Cellular automata can also operate in two or three dimensions, and can use a number of different colours. But pick the right rule, and even the simplest automata can produce behaviour that is very complex or completely random. The Hungarian mathematician and



All in one: the simple 'rule 110' can perform the same range of calculations as any physical computer.

computer-science pioneer John von Neumann, a predecessor of Wolfram's at the Institute for Advanced Study, toyed with cellular automata in the 1950s. But interest had all but evaporated when Wolfram rediscovered them. "I sent my second paper on the subject to *Nature*," he says. "I got a rejection which I couldn't figure out. Then I realized it was the letter they sent to cranks."

But Wolfram persisted, and in 1984 a review article of his made *Nature*'s cover (S. Wolfram *Nature* **311,** 419–424; 1984). Wolfram and a small band of other scientists and mathematicians were by then showing that cellular automata could model the behaviour of many complex systems. Snowflake growth no longer seemed so mysterious, and fluid turbulence became tractable without recourse to complicated equations. Catalysed by rapid improvements in computing power, interest in the field of complex-systems research mushroomed.

Patterns pending

Modelling using cellular automata remains an important strand within the field of complexity. But from the start, Wolfram felt that his colleagues were missing the point. "Most people were dealing with what I thought were the most mundane aspects," he says. Rather than simply using cellular automata to mimic the behaviour of complex systems, Wolfram was convinced that they could be used to reveal unknown aspects of the systems that they were modelling.

So began Wolfram's withdrawal from the academic community. His energies became increasingly devoted to perfecting software to run his cellular automata, and in 1988 he quit as head of the Center for Complex Systems Research at the University of Illinois at Urbana-Champaign, a post created for him just two years before. His new focus was the company he had founded in 1987, Wolfram Research, which was by then ready to launch the Mathematica software package. Much more than a means to run cellular automata, this program provides a convenient platform for just about any kind of mathematical operation. Today, it is used by millions of people including scientists, engineers and financial analysts.

While Mathematica has been rising to its present dominant position, Wolfram's labour of love has remained his masterwork on the power of cellular automata and other simple systems. But it is a love that he has largely kept to himself. "Interaction slows things down," he says. Peer review is a "distraction" — indeed, Wolfram seems to think that he has few peers. Just a select few academic friends have been consulted on an occasional basis.

"I trust my judgement," says Wolfram. "I wanted to build a big intellectual structure and explain it in a coherent way. A standalone book is the only way to do so." He has even used his own company to publish the volume. "It harks back to the days of gentleman scientists publishing at their own expense," observes Gregory Chaitin, a mathematician and computer scientist at IBM's Thomas J. Watson Research Center in Yorktown Heights, New York, one of the few to have been consulted by Wolfram.

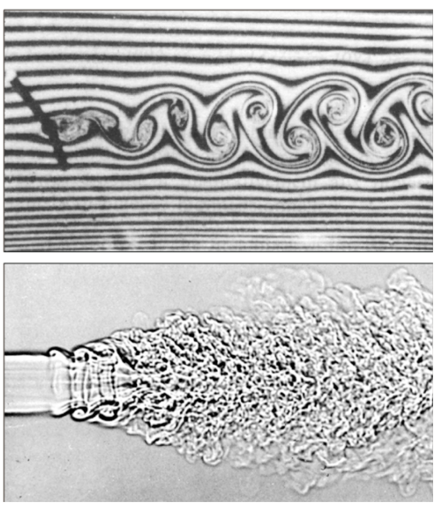
Researchers who have seen the book describe it as provocative and exciting, and some believe it will influence future work in their fields. But others are asking how much is really new, and suggest that Wolfram's enthusiasm for cellular automata has got the better of him.

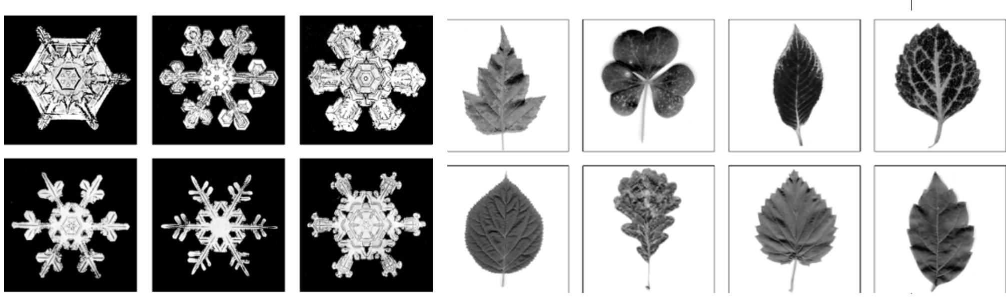
The book describes the behaviour of thousands of different cellular automata and other simple rules, numbered according to a logical scheme. It argues that these systems can yield important insights into phenomena from biological evolution to the fundamental laws of physics. But extraordinary claims demand extraordinary evidence — which many experts feel that Wolfram fails to provide.

Everyone who has read the book says it contains some fascinating nuggets. One result, concerning a system called rule 110, is of particular interest. Rule 110 is very simple — it is one dimensional, uses only two colours, and each square can be updated by looking at just three squares in the previous row. Like all cellular automata, it can be thought of as a computer. The first line is the input, and new outputs are produced after every update. If the squares of one colour are seen as ones and those of the other as zeros, rule 110 can be thought of as doing calculations using binary numbers.

Complexity rules!

Wolfram's book shows that the results of a huge number of possible calculations lie hidden within the output of rule 110, such as computations of natural logarithms and the solutions of differential equations. In the jargon of mathematics, rule 110 is a 'universal computer' — it can perform the same range of calculations as any physical machine. More complex cellular automata have previously been shown to act as universal computers, but Chaitin and other experts are impressed with the demonstration that

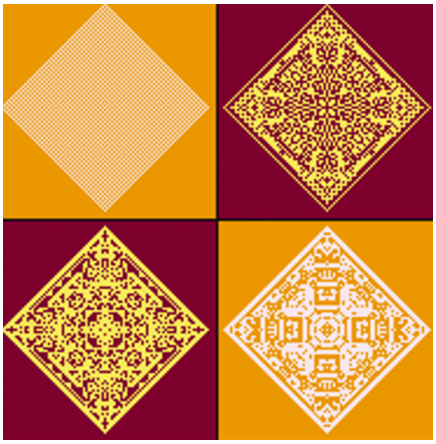


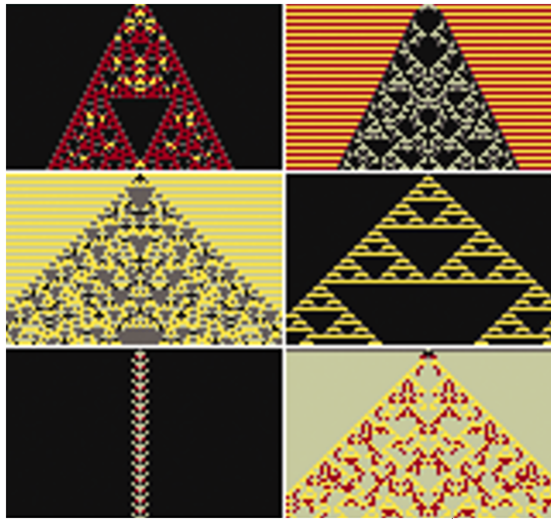


Cellular automata can model a range of phenomena including turbulence, snowflakes and leaves.

very simple cellular automata can behave in the same way.

Terry Sejnowski, a computational neuroscientist at the Salk Institute for Biological Studies in La Jolla, California, another Wolfram confidant, says that the book has made him change the way he thinks about his work. Sejnowski is working on a computer model of a synapse, the gap across which two nerve cells communicate using chemical signals. He had originally entered the positions of key components of the cells by hand, but is now considering modelling the processes by which the components assemble themselves in a living cell, something he previously believed would be too difficult to simulate. "Stephen's book made me ask how the geometry of the cell arises," says Sejnowski. "He has shown this can come from simple rules. Now I'm looking for them."

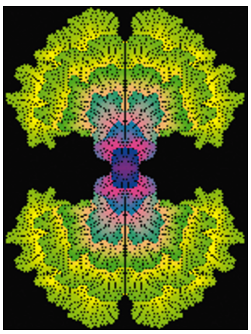




Curiouser and curiouser: Wolfram's book describes the evolution of a variety of automata.

Cell divisions

Others are impressed by the book's scope, even if they disagree with some of its conclusions. Gene Stanley, a physicist at Boston University, has used other mathematical methods to study some of the same systems that Wolfram considers in his text. Stanley does not believe that cellular automata can do everything that Wolfram ascribes to them, but says that the book has persuaded him that they are more than just a curiosity. "This is a much-needed complementary approach," he says. "It's a profound book, perhaps the book of the decade."



But many experts take issue with Wolfram's expansive claims. In the section on fundamental physics, for instance, he presents a simple system, not unlike a cellular automaton, that he believes could be used to describe the fundamental basis of space and time. Wolfram argues that at extremely small scales, space is made up of discrete units, and describes a rule for determining how a structure made up of these units might evolve.

He has tested large numbers of similar models to see which produce the 'right' kind of space — one that is three-dimensional, and obeys Albert Einstein's general theory of relativity. In his book, Wolfram claims that he already has rules that do this, but admits that they cannot yet make the predictions that are possible with Einstein's equations.

Wolfram says that he has deliberately left many details to be pinned down. "I want to see the basic science take root and get a life of its own," he says. Having published the book, he is now planning an evangelical tour of research institutes and universities. "The most important thing now is education," he says. "I want to allow people to use the stuff in the book to do research. Software is coming that allows people to do this." Wolfram the entrepreneur, it seems, operates hand-in-hand with Wolfram the scientific visionary.

But to many, the fact that Wolfram's ideas still lack the predictive power of established theories built on more conventional mathematics is a sign that the wunderkind has come up short. With the book's publication date having been repeatedly pushed back, some speculate that Wolfram has been striving, but never quite succeeding, to pull off his promised scientific revolution. Michael Berry, a theoretical physicist at the University of Bristol, UK, remains unconvinced that Wolfram has done more than embellish the basic idea that simple systems such as cellular automata can generate complexity. "We've known this for 20 years," says Berry. "He'll have some fans, but I think others are going to react strongly against him."

Many in the field of complexity are already queuing up to do so. "I'm very sceptical about whether this is really a whole new way of doing things," says Doyne Farmer, a theoretical physicist at the Santa Fe Institute in New Mexico, the spiritual home of complexity research. Even the rule 110 proof has failed to set the field alight. "Lots of people are showing that all sorts of things are universal computers," says Melanie Mitchell, who works on complex systems and artificial intelligence at Santa Fe. Others point out that many of the phenomena considered by Wolfram have been modelled by other means — and are annoyed by his dismissal of rival approaches.

But within the world of complex systems it is difficult to separate reactions to the man from those to his ideas. One incident in particular has driven a wedge between Wolfram and his former colleagues. The rule 110 proof was actually developed by Matthew Cook, a young mathematician who worked for Wolfram between 1991 and 1998. After leaving Wolfram's employ, Cook presented his results at a conference at the Santa Fe Institute. But details of the talk never made it into the conference proceedings. Wolfram took legal action, arguing that Cook was in breach of agreements that prevented him from publishing until Wolfram's book came out.

Difficult interactions

"We sympathized with Matthew," says one Santa Fe researcher. "Wolfram took a privatized view of science." Cook, now a graduate student at Caltech, says he cannot discuss the matter for legal reasons. Wolfram is similarly reticent — when pressed he describes the incident as "regrettable and best forgotten".

It is not the first time that Wolfram has annoyed complexity researchers, who feel that he routinely fails to recognize the contributions made by others. "He tends to acknowledge people in two-point type," says one researcher. Indeed, *A New Kind of Science* lacks conventional references to prior work — although scientists and mathematicians including Cook are acknowledged in the book's notes section.

Now that the book has finally appeared, Wolfram says that he is looking forward to engaging with his supporters and critics. "I don't want to be a recluse for another 10 years," he says. In the Boston area, from where he is promoting the book, his arrival back on the scene is causing a minor stir. Our meal was interrupted on three occasions. William Hearst, the venture capitalist who inherited the Hearst publishing fortune, popped over to say hello, as did a couple of academics, one from Harvard, the other from the Massachusetts Institute of Technology.

But Wolfram clearly desires more than his current intellectual celebrity. *A New Kind of Science* is his bid for greatness. Now all he has to do is convince a sceptical world that he is really on to something. ■

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