



EXCERPTED FROM

STEPHEN
WOLFRAM
A NEW
KIND OF
SCIENCE

Preface

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Just over twenty years ago I made what at first seemed like a small discovery: a computer experiment of mine showed something I did not expect. But the more I investigated, the more I realized that what I had seen was the beginning of a crack in the very foundations of existing science, and a first clue towards a whole new kind of science.

This book is the culmination of nearly twenty years of work that I have done to develop that new kind of science. I had never expected it would take anything like as long, but I have discovered vastly more than I ever thought possible, and in fact what I have done now touches almost every existing area of science, and quite a bit besides.

In the early years, I did as I had done before as a scientist, and published accounts of my ongoing work in the scientific literature. But although what I wrote seemed to be very well received, I gradually came to realize 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 had finished, and was ready to present everything in a single coherent way. Fifteen years later this book is the result. And with it my hope is to share what I have done with as wide a range of scientists and non-scientists as possible.

In modern times it has been almost unheard of for genuinely new science to be presented for the first time in a book that can be read by non-scientists. For progress in science has mostly tended to take place

in small steps that cannot reasonably be explained without relying on specialized technical knowledge of what has gone before.

But to develop the new kind of science that I describe in this book I have had no choice but to take several large steps at once, and in doing so 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.

In some ways it might have been easier for me to present what I have done in some kind of new technical formalism. But instead I have chosen to spend the effort to take things to the point where they are clear enough to be explained quite fully just in ordinary language and pictures.

Unfortunately, however, this will no doubt mean that there are some—particularly from the existing sciences—who will at first assume that their existing technical knowledge must somehow already cover whatever is in this book. And a few, I fear, will stop at that point, and choose to learn no more. But many, I hope, will at least look at the book long enough to begin to be surprised by what it actually says.

At first probably they will think that parts of it cannot possibly be correct—for they seem so at odds with existing science. And indeed if I myself were just to pick up this book today without having spent the past twenty years thinking about its contents, I have little doubt that I too would not believe many of the things it says.

But the computer experiments on which the science in the book is ultimately based are easy to check on any modern computer. And almost all the arguments in the book—while often not conceptually simple—require no specialized scientific or other knowledge to follow.

Yet it has certainly taken me years to come to terms with the conclusions I have reached. And while I hope that all the effort I have put into presentation in this book will make it easier for others, I do not expect it to be a quick process. For to absorb in any real way what the book has to say requires a fairly major shift in intuition and thinking.

But the most important first step, I believe, is just to recognize what is involved. For though there are connections of all sorts, this book is first and foremost about a fundamentally new intellectual structure, that needs to be understood in its own terms, and cannot reasonably be fit into any existing framework.

It has been a great challenge for me to capture the things I have discovered over the past twenty years in a book of manageable size. And to do so I have often ended up compressing into a page or even a paragraph the essence of what a chapter or even a book could have been written about.

In the quarter million or so words of the main text my emphasis is on communicating the core of my ideas and discoveries—as well as indicating a little of how I came to them. The last three hundred or so pages of the book—themselves another quarter million or so words—supplement the main text with many historical and technical notes, and also summarize more discoveries. The notes that begin on page 849 address some specific issues about reading this book.

Throughout the book my primary concern is with basic science and fundamental issues. But building on the foundations in the book there are a vast array of applications—both conceptual and practical—that can now be developed.

No doubt some will come quickly. But most will probably take decades to emerge. 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. And in the end most of what now seems surprising and remarkable in the book will come to seem familiar and commonplace.

But for me what has always been most important is the actual process of discovery. For I know of nothing as profoundly exciting as to glimpse for the first time some new and basic truth. And now that I have finished building the intellectual structure that I describe in this book it is my hope that those who read these words can share in the excitement I have had in making the discoveries that were involved.

Stephen Wolfram
January 15, 2002

The creation of this book and the science it describes has been a vast personal undertaking, spanning the better part of half my life so far. And for it to all have been even remotely possible has required a series of particular personal circumstances. Foremost among them is that I have lived at the moment in history when technology has first made it possible to do the kinds of things I have done. But also crucial has been that my early successes in science and business have for more than twenty years allowed me to be free to pursue the personal intellectual objectives I have chosen.

That by my late teenage years I had already become established in science was what originally provided the personal confidence and practical situation that made it possible for me to embark on an intellectual project as ambitious as this. My early experiences—particularly in physics and computing—were crucial in pointing me in the basic direction I took. My work in designing and documenting *Mathematica* and its forerunners was central in developing for me a certain definite pattern of clear thinking. My experiences in business were also important in helping me form a capacity for making strategic intellectual decisions. And the fact that for most of my life I have tried to learn as broadly and deeply as possible about science and other fields has provided me a crucial base of knowledge. But more than anything else what has finally allowed me to create the new kind of science in this book is *Mathematica*. For while building *Mathematica* has taken a considerable amount of my time, I would without it as a tool never have been able to do the vast majority of what is now in this book.

In my early years I was very much a part of the traditional scientific community. But had I remained there I have little doubt that I would never have been able to create something of the magnitude that I describe in this book. For even just to spend so many years on a single project outside of existing disciplines—and without publishing anything about it—would likely have become impossible even in the highly favorable academic circumstances in which I found myself.

But with the commercial success of *Mathematica* and Wolfram Research there have for many years not been any such issues for me. And indeed, within my company I have been able to build up a remarkable group of people—who have supported my efforts in all sorts of ways. Over the past fifteen years hundreds of members of our R&D and engineering groups have worked to take my ideas for *Mathematica* and turn them into finished software that I and millions of others rely on every day. And at one time or another almost every major department of my company has provided help that has been crucial to some aspect of the creation or production of this book.

Yet what is probably most striking is that even in my role as CEO of a highly active company I have for more than ten years been able to devote the large amounts of time that have been required to write this book and develop the science it describes. And more than anything else, what has made this possible is the outstanding team that has helped manage the ongoing operations of the company—especially our current executive committee: George Beck, Roger Germundsson, Theodore Gray, Becky Porth, Brenda Skelly, Tom Wickham-Jones and my brother Conrad Wolfram.

To pursue a project of the length and intensity of this book would not have been possible without the great personal support of my family and friends. Particularly crucial have been my wife—who has contributed both directly and indirectly to many aspects of the form

and content of this book, and my children—whose excitement about the world has provided continual encouragement and stimulation. Also important—especially in my youth—were my parents, who supported my early interests and direction.

Like almost any highly creative project, the writing of this book has ultimately been a quite solitary and personal matter. But I have been fortunate over the years to employ a variety of talented assistants, who have helped the project in many different ways: Eric Berg (project management, 2000–2001), Jason Cawley (historical and philosophical issues, 2001–2002 and before), Matthew Cook (technical content, particularly constructions and proofs, 1991–1998), Andrew de Laix (technical content and book production systems, 1998–2002), Matthew Frank (mathematical and historical issues, 2001–2002), Andrea Gerlach (fact finding and checking, 1999–2002), David Hillman (constructions and other technical content, 1997–2001), Scott Koranda (book production systems and project management, 1996–1998), Ed Pegg, Jr. (technical content, 2000–2002), Todd Rowland (mathematical issues, 2001–2002), Malgorzata Strzebonska (graphics finishing, 1997–2002), Matthew Szudzik (mathematical issues, 1998–2000, 2001), Øyvind Tafjord (physics and other technical issues, 2001–2002), Kelli Wendt (project management, 2001–2002), Erik Winfree (software development, 1991–1992). Other members of Wolfram Research and Wolfram Media who have made particularly significant contributions include: Larry Adelston (book layout, 2000–2002), George Beck (project management oversight, 2001–2002 and before), John Bonadies (cover design and other issues, 1995, 1991–1999), Cat Boucher (project management, 2001–2002), Jean Buck (library research 1991–1999; many internal and external issues 1999–2002), Jeremy Davis (design, 2000–2002), Deb Forgacs (library research, 2000–2002), Thomasanna Hail (project management assistance, 2001), Yu He (technical issues, 1991–1992), Andy Hunt (font design, 1997–2002), Janice Hunter (book distribution, 2000–2002), André Kuzniarek (book design and production, 1991–2002), Richard Miske (book layout, 2001–2002), Jan Progen (proofreading, 1997–2002), David Reiss (external communications, 2001–2002), Patrick Rice (book build automation, 2001–2002), Brenda Skelly (manufacturing management, 2001–2002 and before), Caroline Small (document quality assurance, 2001), Michael Trott (occasional technical issues, 1994–2002), Allan Wylde (publishing issues, 1998–1999). (See also the colophon at the very end of the book.) My administrative and computer systems assistants have also been crucial in allowing me to maintain the high level of personal productivity needed to pursue and complete this project.

In developing the new kind of science in this book I have benefitted in many ways from the worldwide intellectual community. I have always worked hard to learn as many fields as possible as deeply as I can—and to keep abreast of new developments that emerge. Part of what has allowed me to do this is reading an immense number of books, articles and websites. But over the years what has also been important is that I have interacted personally with a great many individuals, and I have been fortunate that my position in science and technology has brought me into contact at one time or another with the leaders of almost every major technical field.

In the early and mid-1980s I did collaborative work relevant to this book—some published, some unpublished—with several people: Richard Feynman (foundations of physics and computing), Olivier Martin (additive cellular automata), John Milnor (mathematics of

cellular automata), Andrew Odlyzko (additive cellular automata), Norman Packard (2D cellular automata) and Jim Salem (cellular automaton fluids).

Over the course of the past twenty years I have learned many things relevant to this book from many people. Sometimes I have asked specific questions and got specific answers. Sometimes discussions separated by months or years have gradually made me come to understand something. Sometimes just a single discussion has caused me to learn an important fact or piece of history—or has clarified limitations of some particular field. And sometimes a question asked of me has led me to discover something or to see how to present something better. In all I recall nearly three hundred people who have helped me in these kinds of ways in the past twenty years (this does not include people—especially from the physics community—with whom my main interactions were before 1981, or those with whom my interactions have mostly been about *Mathematica* or the business of Wolfram Research): Ralph Abraham, Victor Adamchik, Ron Adrian, Guenther Ahlers, Berni Alder, Jan Ambjørn, John Baez, Jim Bailey, Igor Bakshee, Mary Barsony, Andrej Bauer, George Beck, Charles Bennett, Michael Berry, Philippe Binder, Lenore Blum, Manuel Blum, Bruce Boghosian, Enrico Bombieri, Phil Boyland, William Bricken, Bruno Buchberger, Art Burks, David Campbell, John Campbell, Chris Carlson, Pete Carruthers, Forrest Carter, Elise Cawley, Greg Chaitin, Steve Christensen, David Chudnovsky, Gregory Chudnovsky, John Conway, Barbara Cooper, Jack Cowan, Richard Crandall, Jim Crutchfield, Karel Culik, Predrag Cvitanović, Gautam Dasgupta, Roger Dashes, Martin Davis, Richard Dawkins, David Deutsch, Kee Dewdney, Persi Diaconis, Whitfield Diffie, Freeman Dyson, Paul Erdős, Benson Farb, Doyne Farmer, Mitchell Feigenbaum, Carl Feynman, Richard Feynman, David Finkelstein, Michael Fisher, Mike Foale, Joseph Ford, John Franks, Ed Fredkin, Harvey Friedman, Uriel Frisch, Peter Gacs, Jill Gardner, Laurie Gay, Todd Gayley, Richard Gaylord, Murray Gell-Mann, Roger Germundsson, Etienne Ghys, Don Glaser, Nigel Goldenfeld, Shafi Goldwasser, Beatrice Golomb, Solomon Golomb, Bill Gosper, Peter Grassberger, Alfred Gray, Jeremy Gray, John Gray, Theodore Gray, David Griffeth, Misha Gromov, David Gross, John Guckenheimer, Charlie Gunn, Howard Gutowitz, Hyman Hartman, Jeff Harvey, Brosl Hasslacher, David Hawkins, Gustav Hedlund, Danny Hillis, Pierre Hohenberg, John Holland, John Hopfield, Bernardo Huberman, Alfred Hübler, Dominique d’Humières, Lyman Hurd, Ken Iverson, Raymond Jeanloz, Erica Jen, Leo Kadanoff, Dave Kammeyer, Kuni Kaneko, Stuart Kauffman, Karen Kavanagh, Jerry Keiper, Evelyn Fox Keller, Veikko Keränen, Scott Kirkpatrick, Sergiu Klainerman, Rob Knapp, Don Knuth, Rocky Kolb, John Koza, Bob Kraichnan, Yoshi Kuramoto, Jeff Lagarias, Rolf Landauer, Jim Langer, Chris Langton, Joel Lebowitz, David Levermore, Leonid Levin, Silvio Levy, Steven Levy, Debra Lewis, Wentian Li, Albert Libchaber, David Librik, Dan Lichtblau, Doug Lind, Aridist Lindenmayer, Kristian Lindgren, Chris Lindsey, Ed Lorenz, Saunders Mac Lane, Roman Mäder, Janice Malouf, Benoit Mandelbrot, Norman Margolus, Oleg Marichev, Olivier Martin, Yuri Matiyasevich, John Maynard Smith, Curt McMullen, Hans Meinhardt, Michel Mendès France, Nick Metropolis, John Miller, John Milnor, Marvin Minsky, Don Mitchell, Kim Molvig, John Moussouris, Walter Munk, Jim Murray, Lee Neuwirth, Alan Newell, Mats Nordahl, John Novak, Andrew Odlyzko, Steve Orszag, George Oster, Peter Overmann, Norman

Packard, Heinz Pagels, Leonard Parker, Roger Payne, Holly Peck, Hans-Otto Peitgen, Roger Penrose, Alan Perelson, Malcolm Perry, Charlie Peskin, David Pines, Simon Plouffe, Yves Pomeau, Bjorn Poonen, Marian Pour-El, Kendall Preston, Lutz Prieese, Ilya Prigogine, Itamar Procaccia, Charles Radin, Tom Ray, Jim Reeds, John Reif, David Reiss, Stanley Reiter, Ken Ribet, Jane Richardson, Ron Rivest, Igor Rivin, Terry Robb, Julia Robinson, Raphael Robinson, Robert Rosen, Gian-Carlo Rota, Lee Rubel, Rudy Rucker, David Ruelle, Jim Salem, Len Sander, Dana Scott, Terry Sejnowski, Rob Shaw, Tim Shaw, Steve Shenker, Bev Sher, Tsutomu Shimomura, Peter Shor, Brian Silverman, Karl Sims, Steven Skiena, Steve Smale, Caroline Small, Alvy Ray Smith, Bruce Smith, Lee Smolin, Mark Sofroniou, Gene Stanley, Ken Steiglitz, Dan Stein, Paul Steinhart, Pat Suppes, Gerry Sussman, Klaus Sutner, Noel Swerdlow, Harry Swinney, Bart Taub, David Terr, René Thom, Bill Thurston, Tom Toffoli, Alar Toomre, Russell Towle, Amos Tversky, Stan Ulam, Leslie Valiant, Léon van Hove, Ilan Vardi, Hal Varian, Geerat Vermeij, Gerard Vichniac, Stan Wagon, Bob Wainwright, Bruce Walker, Denis Weaire, Eric Weisstein, Paul Wellin, Caroline Wickham-Jones, Tom Wickham-Jones, Amie Wilkinson, Stephen Willson, Jack Wisdom, Rob Wolff, Alexander Wolfram, Conrad Wolfram, Sybil Wolfram, Lewis Wolpert, Michael Woodford, Larry Wos, Larry Yaffe, Victor Yakhot, Jim Yorke, John Zerolis, Richard Zippel, George Zweig, Helio Zwi. In addition to those with whom I have had direct contact, other individuals have provided input indirectly through my assistants or others (excluding photograph sources listed in the colophon): Bill Beyer, Sheila Blair, Victor Dan, Brent Daniel, Noam Elkies, Peter Falloon, Erich Friedman, Jochen Gerber, Branko Grünbaum, Richard Guy, Michel Janssen, Martin Kraus, Temur Kutsia, Richard Langley, Bernd Löchner, Crista Malick, Brendan McKay, Thomas Scanlon, Rob Scharein, Marjorie Senechal, Marc Sher, David Singmaster, Neil Sloane, Milton Van Dyke, Bob Veroff, Curtis Wilson, Mirek Wójtowicz. Librarians at many institutions—especially the University of Illinois—have often helped my assistants in locating materials. Many individuals at Wolfram Research have also contributed their collective breadth of knowledge on diverse smaller questions.

I began serious development of ideas that eventually led to this book in 1981, and until 1988 I continued to be a member of various academic institutions: California Institute of Technology (Physics Department, 1978–1982), Institute for Advanced Study, Princeton (School of Natural Sciences, 1982–1986), University of Illinois (Center for Complex Systems Research, and Departments of Physics, Mathematics and Computer Science, 1986–1988). I built up successively larger research groups at these institutions, and both the scientific and other members of these groups made a variety of contributions to my work.

In the early to mid-1980s I was a consultant to a number of organizations. The primary ones at which I pursued projects that helped me in formulating issues for this book were Bell Laboratories, Los Alamos National Laboratory and Thinking Machines Corporation. In the period before 1986 a few of my projects received incidental support from various parts of the U.S. government, and I made use of early workstation computers given to me by Sun Microsystems. The MacArthur Fellowship that I received in May 1981 was an important element of personal support, and in fact it was a few months after this award that I made the decision to focus

my work towards what would eventually become the new kind of science in this book.

In the early years of the project—and before I became independent of academia—there were a number of individuals who showed particular foresight in arranging for organizational support or publication of my work, including: George Bell, Bill Brinkman, Roger Dashen, Marvin Denicoff, Herman Feshbach, John Gage, Murray Gell-Mann, Paul Halmos, Sheryl Handler, Danny Hillis, Bob Kraichnan, Oscar Lanford, Joel Lebowitz, Elliott Lieb, John Maddox, K. K. Phua, David Pines, Gian-Carlo Rota, Mike Schlesinger, Ralph Simmons, Larry Smarr, Harry Woolf.

Many influences early in my life are no doubt reflected in one way or another in this book. That my mother was an Oxford philosophy don caused me in my youth to be exposed to a certain amount of academic philosophy. My classical English education—in elementary school (Dragon School) and high school (Eton)—emphasized such pursuits as writing, and exposed me to a certain range of subjects, a remarkable fraction of which have ended up being useful, especially in the historical research for this book. My brief times in college (Oxford) and graduate school (Caltech) enhanced my enthusiasm and confidence in science, and allowed me rapidly to begin life as a professional scientist. In the years that I was a member of the theoretical physics community a great many people provided encouragement, and contributed to my understanding of science and how it should be done. Among those friends, colleagues, teachers and others from before 1981 from whom I learned things relevant for the methods, content or writing of this book were: Ed Berger, Euan Cameron, Chris Cole, Armand D'Angour,

Richard Feynman, Rick Field, Geoffrey Fox, Philip Gladstone, Nathan Isgur, Nicholas Kermack, Rocky Kolb, Chris Llewellyn Smith, David Longrigg, Rob Pike, David Politzer, Dick Roberts, Norman Routledge, George Rutter, Ken Spencer, Christopher Stuart-Clark, Tony Terrano, Tini Veltman, Peregrine Williams, Hugo Wolfram, Sybil Wolfram, Larry Yaffe, George Zweig.

To complete a project of the magnitude of this book requires extreme personal focus. And to maintain this, I have for most of the past decade been an almost complete recluse, attending almost no outside events, and interacting mainly just with family, friends, assistants and senior staff at my company. During this period it has nevertheless provided important encouragement to see that even without my personal presence, my earlier work in science—and even more so my work on *Mathematica*—has had an increasingly great impact on the world. It has also been a continuing source of further encouragement to see just how broadly and deeply the worldwide *Mathematica* community has been able to make use of the fundamental ideas that I have embodied in *Mathematica*.

To write this book has taken me more than ten years of almost continuous work, more than a hundred million keystrokes, and more than a hundred mouse miles. I have accumulated tens of gigabytes and hundreds of thousands of pages of *Mathematica* notebooks. I have executed nearly a million lines of *Mathematica* input, and altogether more than a million billion computer operations. But now that the task is finally done—and I have written down at least the main elements of my discoveries so far—I look forward to everything that is now possible.