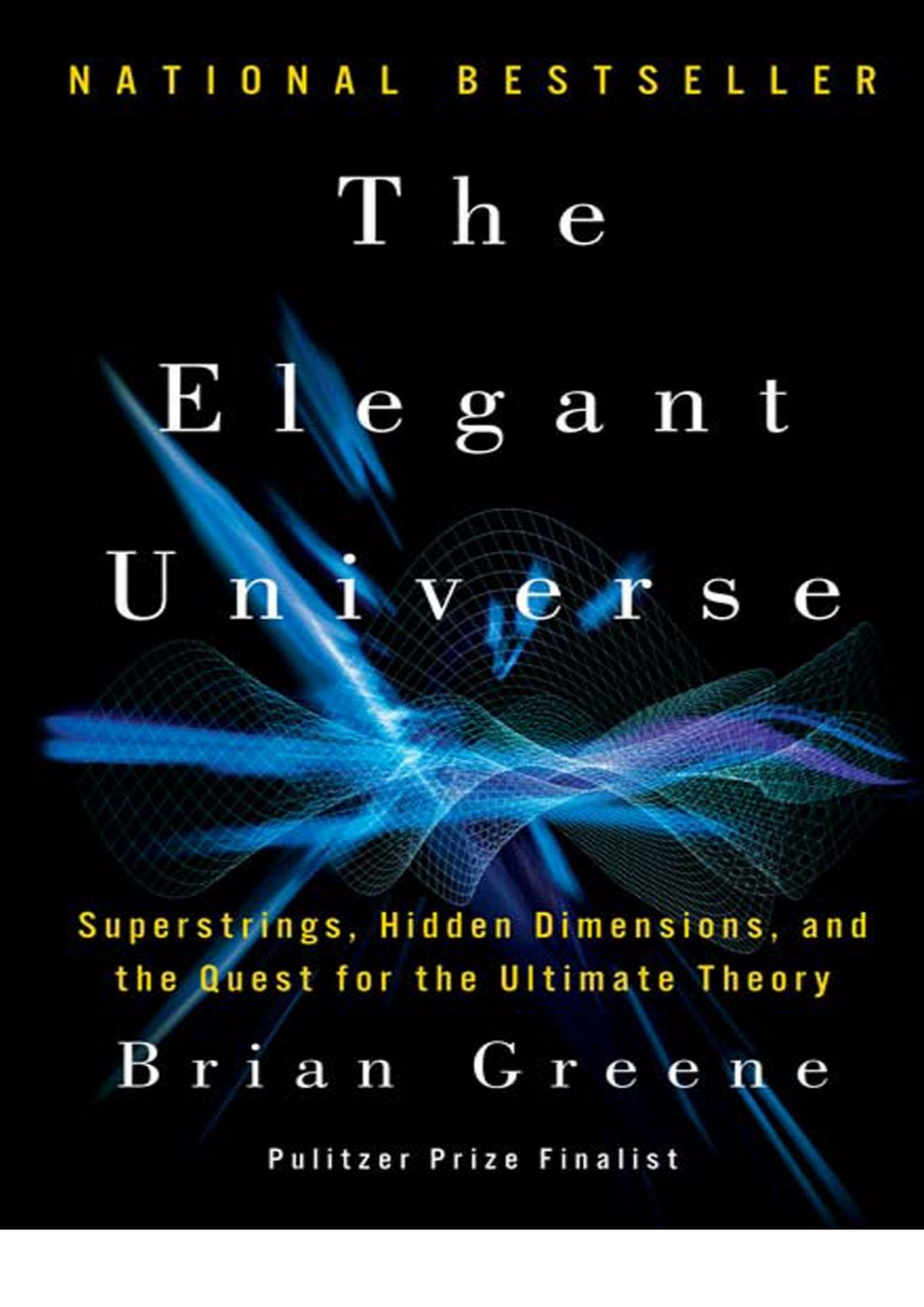


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The
Elegant
Universe

The background of the cover features a complex, abstract design. It consists of several overlapping, wavy, translucent surfaces in shades of blue and purple. These surfaces are overlaid with a fine, white grid pattern, creating a sense of depth and movement. The overall effect is reminiscent of a digital or scientific visualization, possibly representing a string theory concept like a superstring or a hidden dimension.

Superstrings, Hidden Dimensions, and
the Quest for the Ultimate Theory

Brian Greene

Pulitzer Prize Finalist

Superstrings, Hidden Dimensions, and the Quest for the Ultimate Theory

Brian Greene



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*To my mother and the memory of my father,
with love and gratitude*

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Preface

During the last thirty years of his life, Albert Einstein sought relentlessly for a so-called unified field theory—a theory capable of describing nature's forces within a single, all-encompassing, coherent framework. Einstein was not motivated by the things we often associate with scientific undertaking, such as trying to explain this or that piece of experimental data. Instead, he was driven by a passionate belief that the deepest understanding of the universe would reveal its truest wonder: the simplicity and power of the principles on which it is based. Einstein wanted to illuminate the workings of the universe with a clarity never before achieved, allowing us all to stand in awe of its sheer beauty and elegance.

Einstein never realized this dream, in large part because the deck was stacked against him: In his day, a number of essential features of matter and the forces of nature were either unknown or, at best, poorly understood. But during the past half-century, physicists of each new generation—through fits and starts, and diversions down blind alleys—have been building steadily on the discoveries of their predecessors to piece together an ever fuller understanding of how the universe works. And now, long after Einstein articulated his quest for a unified theory but came up empty-handed, physicists believe they have finally found a framework for stitching these insights together into a seamless whole—a single theory that, in principle, is capable of describing all physical phenomena. The theory, *superstring theory*, is the subject of this book.

I wrote *The Elegant Universe* in an attempt to make the remarkable insights emerging from the forefront of physics research accessible to a broad spectrum of readers, especially those with no training in mathematics or physics. Through public lectures on superstring theory I have given over the past few years, I have witnessed a widespread yearning to understand what current research says about the fundamental laws of the universe, how these laws require a monumental restructuring of our conception of the cosmos, and what challenges lie ahead in the ongoing quest for the ultimate theory. I hope that, by explaining the major achievements of physics going back to Einstein and Heisenberg and describing how their discoveries have grandly flowered through the breakthroughs of our age, this book will both enrich and satisfy this curiosity.

I also hope that *The Elegant Universe* will be of interest to readers who do have some scientific background. For science students and teachers, I hope this book will crystallize some of the foundational material of modern physics, such as special relativity, general relativity, and quantum mechanics, while conveying the contagious excitement of researchers closing in on the long-sought unified theory. For the avid reader of popular science, I have tried to explain many of the exhilarating advances in our understanding of the cosmos that have come to light during the last decade. And for my colleagues in other scientific disciplines, I hope this book will give an honest and balanced sense of why string theorists are so enthusiastic about the progress being made in the search for the ultimate theory of nature.

Superstring theory casts a wide net. It is a broad and deep subject that draws on many of the central discoveries in physics. Since the theory unifies the laws of the large and of the small, laws that govern physics out to the farthest reaches of the cosmos and down to the smallest speck of matter, there are many avenues by which one can approach the subject. I have chosen to focus on our evolving understanding of space and time. I find this to be an especially gripping developmental path, one that

cuts a rich and fascinating swath through the essential new insights. Einstein showed the world that space and time behave in astoundingly unfamiliar ways. Now, cutting-edge research has integrated his discoveries into a quantum universe with numerous hidden dimensions coiled into the fabric of the cosmos—dimensions whose lavishly entwined geometry may well hold the key to some of the most profound questions ever posed. Although some of these concepts are subtle, we will see that they can be grasped through down-to-earth analogies. And when these ideas are understood, they provide a startling and revolutionary perspective on the universe.

Throughout this book, I have tried to stay close to the science while giving the reader an intuitive understanding—often through analogy and metaphor—of how scientists have reached the current conception of the cosmos. Although I avoid technical language and equations, because of the radical new concepts involved the reader may need to pause now and then, to mull over a section here or ponder an explanation there, in order to follow the progression of ideas fully. A few sections of Part IV (focusing on the most recent developments) are a bit more abstract than the rest; I have taken care to forewarn the reader about these sections and to structure the text so that they can be skimmed or skipped with minimal impact on the book's logical flow. I have included a glossary of scientific terms for an easy and accessible reminder of ideas introduced in the main text. Although the more casual reader may wish to skip the endnotes completely, the more diligent reader will find in the notes amplifications of points made in the text, clarifications of ideas that have been simplified in the text, as well as a few technical excursions for those with mathematical training.

I owe thanks to many people for their help during the writing of this book. David Steinhardt read the manuscript with great care and generously provided sharp editorial insights and invaluable encouragement. David Morrison, Ken Vineberg, Raphael Kasper, Nicholas Boles, Steven Carlip, Arthur Greenspoon, David Mermin, Michael Popowits, and Shani Offen read the manuscript closely and offered detailed reactions and suggestions that greatly enhanced the presentation. Others who read all or part of the manuscript and offered advice and encouragement are Paul Aspinwall, Persis Dreier, Michael Duff, Kurt Gottfried, Joshua Greene, Teddy Jefferson, Marc Kamionkowski, Yakov Kantor, Andras Kovacs, David Lee, Megan McEwen, Nari Mistry, Hasan Padamsee, Ronen Plesser, Massimo Porrati, Fred Sherry, Lars Straeter, Steven Strogatz, Andrew Strominger, Henry Tye, Cumrun Vafa, and Gabriele Veneziano. I owe special thanks to Raphael Gunner for, among many other things, his insightful criticisms at an early stage of writing that helped to shape the overall form of the book, and to Robert Malley for his gentle but persistent encouragement to go beyond thinking about the book and to put "pen to paper." Steven Weinberg and Sidney Coleman offered valuable advice and assistance, and it is a pleasure to acknowledge many helpful interactions with Carol Archer, Vicki Carstens, David Cassel, Anne Coyle, Michael Duncan, Jane Forman, Wendy Greene, Susan Green, Erik Jendresen, Gary Kass, Shiva Kumar, Robert Mawhinney, Pam Morehouse, Pierre Ramond, Amanda Salles, and Eero Simoncelli. I am indebted to Costas Efthimiou for his help in fact-checking and reference-finding, and for turning my initial sketches into line drawings from which Tom Rockwell created—with the patience of a saint and a masterful artistic eye—the figures that illustrate the text. I also thank Andrew Hanson and Jim Sethna for their help in preparing a few of the specialized figures.

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I am happy to acknowledge the penetrating insights and invaluable suggestions of Angela Voder Lippe and the sharp sensitivity to detail of Traci Nagle, my editors at W. W. Norton, both of whom significantly enhanced the clarity of the presentation. I also thank my literary agents, John Brockman and Katinka Matson, for their expert guidance in shepherding the book from inception to publication.

For generously supporting my research in theoretical physics for more than a decade and a half,

For generously supporting my research in theoretical physics for more than a decade and a half, I gratefully acknowledge the National Science Foundation, the Alfred P. Sloan Foundation, and the U.S. Department of Energy. It is perhaps not surprising that my own research has focused on the impact superstring theory has on our conception of space and time, and in a couple of the later chapters describe some of the discoveries in which I had the fortune to take part. Although I hope the reader will enjoy reading these "inside" accounts, I realize that they may leave an exaggerated impression of the role I have played in the development of superstring theory. So let me take this opportunity to acknowledge the more than one thousand physicists around the world who are crucial and dedicated participants in the effort to fashion the ultimate theory of the universe. I apologize to all whose work is not included in this account; this merely reflects the thematic perspective I have chosen and the length limitations of a general presentation.

Finally, I owe heartfelt thanks to Ellen Archer for her unwavering love and support, without which this book would not have been written.

The Edge of Knowledge

Tied Up with String

Calling it a cover-up would be far too dramatic. But for more than half a century—even in the midst of some of the greatest scientific achievements in history—physicists have been quietly aware of a dark cloud looming on a distant horizon. The problem is this: There are two foundational pillars upon which modern physics rests. One is Albert Einstein's general relativity, which provides a theoretical framework for understanding the universe on the largest of scales: stars, galaxies, clusters of galaxies, and beyond to the immense expanse of the universe itself. The other is quantum mechanics, which provides a theoretical framework for understanding the universe on the smallest of scales: molecules, atoms, and all the way down to subatomic particles like electrons and quarks. Through years of research, physicists have experimentally confirmed to almost unimaginable accuracy virtually all predictions made by each of these theories. But these same theoretical tools inexorably lead to another disturbing conclusion: As they are currently formulated, general relativity and quantum mechanics *cannot both be right*. The two theories underlying the tremendous progress of physics during the last hundred years—progress that has explained the expansion of the heavens and the fundamental structure of matter—are mutually incompatible.

If you have not heard previously about this ferocious antagonism you may be wondering why. The answer is not hard to come by. In all but the most extreme situations, physicists study things that are either small and light (like atoms and their constituents) or things that are huge and heavy (like stars and galaxies), but not both. This means that they need use only quantum mechanics *or* only general relativity and can, with a furtive glance, shrug off the barking admonition of the other. For fifty years this approach has not been quite as blissful as ignorance, but it has been pretty close.

But the universe *can* be extreme. In the central depths of a black hole an enormous mass is crushed to a minuscule size. At the moment of the big bang the whole of the universe erupted from a microscopic nugget whose size makes a grain of sand look colossal. These are realms that are tiny and yet incredibly massive, therefore requiring that both quantum mechanics and general relativity simultaneously be brought to bear. For reasons that will become increasingly clear as we proceed, the equations of general relativity and quantum mechanics, when combined, begin to shake, rattle, and gush with steam like a red-lined automobile. Put less figuratively, well-posed physical questions elicit nonsensical answers from the unhappy amalgam of these two theories. Even if you are willing to keep the deep interior of a black hole and the beginning of the universe shrouded in mystery, you can't help feeling that the hostility between quantum mechanics and general relativity cries out for a deeper level of understanding. Can it really be that the universe at its most fundamental level is divided, requiring one set of laws when things are large and a different, incompatible set when things are small?

Superstring theory, a young upstart compared with the venerable edifices of quantum mechanics and general relativity, answers with a resounding no. Intense research over the past decade by physicists and mathematicians around the world has revealed that this new approach to describing matter at its most fundamental level resolves the tension between general relativity and quantum mechanics. In fact, superstring theory shows more: Within this new framework, general relativity and quantum mechanics *require one another* for the theory to make sense. According to superstring

theory, the marriage of the laws of the large and the small is not only happy but inevitable.

~~That's part of the good news. But superstring theory—string theory, for short—takes this union~~ one giant step further. For three decades, Einstein sought a unified theory of physics, one that would interweave all of nature's forces and material constituents within a single theoretical tapestry. He failed. Now, at the dawn of the new millennium, proponents of string theory claim that the threads of this elusive unified tapestry finally have been revealed. String theory has the potential to show that all of the wondrous happenings in the universe—from the frantic dance of subatomic quarks to the state waltz of orbiting binary stars, from the primordial fireball of the big bang to the majestic swirl of heavenly galaxies—are reflections of one grand physical principle, one master equation.

Because these features of string theory require that we drastically change our understanding of space, time, and matter, they will take some time to get used to, to sink in at a comfortable level. But as shall become clear, when seen in its proper context, string theory emerges as a dramatic yet natural outgrowth of the revolutionary discoveries of physics during the past hundred years. In fact, we shall see that the conflict between general relativity and quantum mechanics is actually not the first, but the third in a sequence of pivotal conflicts encountered during the past century, each of whose resolutions has resulted in a stunning revision of our understanding of the universe.

The Three Conflicts

The first conflict, recognized as far back as the late 1800s, concerns puzzling properties of the motion of light. Briefly put, according to Isaac Newton's laws of motion, if you run fast enough you can catch up with a departing beam of light, whereas according to James Clerk Maxwell's laws of electromagnetism, you can't. As we will discuss in Chapter 2, Einstein resolved this conflict through his theory of special relativity, and in so doing completely overturned our understanding of space and time. According to special relativity, no longer can space and time be thought of as universal concepts set in stone, experienced identically by everyone. Rather, space and time emerged from Einstein's reworking as malleable constructs whose form and appearance depend on one's state of motion.

The development of special relativity immediately set the stage for the second conflict. One conclusion of Einstein's work is that no object—in fact, no influence or disturbance of any sort—can travel faster than the speed of light. But, as we shall discuss in Chapter 3, Newton's experimentally successful and intuitively pleasing universal theory of gravitation involves influences that are transmitted over vast distances of space *instantaneously*. It was Einstein, again, who stepped in and resolved the conflict by offering a new conception of gravity with his 1915 general theory of relativity. Just as special relativity overturned previous conceptions of space and time, so too did general relativity. Not only are space and time influenced by one's state of motion, but they can warp and curve in response to the presence of matter or energy. Such distortions to the fabric of space and time, as we shall see, transmit the force of gravity from one place to another. Space and time, therefore, can no longer be thought of as an inert backdrop on which the events of the universe play themselves out; rather, through special and then general relativity, they are intimate players in the events themselves.

Once again the pattern repeated itself: The discovery of general relativity, while resolving one conflict, led to another. Over the course of the three decades beginning in 1900, physicists developed quantum mechanics (discussed in Chapter 4) in response to a number of glaring problems that arose when nineteenth-century conceptions of physics were applied to the microscopic world. And as mentioned above, the third and deepest conflict arises from the incompatibility between quantum mechanics and general relativity. As we will see in Chapter 5, the gently curving geometrical form of

space emerging from general relativity is at loggerheads with the frantic, roiling, microscopic behavior of the universe implied by quantum mechanics. As it was not until the mid-1980s that string theory offered a resolution, this conflict is rightly called the central problem of modern physics. Moreover, building on special and general relativity, string theory requires its own severe revamping of our conceptions of space and time. For example, most of us take for granted that our universe has three spatial dimensions. But this is not so according to string theory, which claims that our universe has many more dimensions than meet the eye—dimensions that are tightly curled into the folds of the fabric of the cosmos. So central are these remarkable insights into the nature of space and time that we shall use them as a guiding theme in all that follows. String theory, in a real sense, is the story of space and time since Einstein.

To appreciate what string theory actually is, we need to take a step back and briefly describe what we have learned during the last century about the microscopic structure of the universe.

The Universe at Its Smallest: What We Know about Matter

The ancient Greeks surmised that the stuff of the universe was made up of tiny "uncuttable" ingredients that they called *atoms*. Just as the enormous number of words in an alphabetic language is built up from the wealth of combinations of a small number of letters, they guessed that the vast range of material objects might also result from combinations of a small number of distinct, elementary building blocks. It was a prescient guess. More than 2,000 years later we still believe it to be true, although the identity of the most fundamental units has gone through numerous revisions. In the nineteenth century scientists showed that many familiar substances such as oxygen and carbon had a smallest recognizable constituent; following in the tradition laid down by the Greeks, they called these *atoms*. The name stuck, but history has shown it to be a misnomer, since atoms surely are "cuttable." By the early 1930s the collective works of J. J. Thomson, Ernest Rutherford, Niels Bohr, and James Chadwick had established the solar system–like atomic model with which most of us are familiar. Far from being the most elementary material constituent, atoms consist of a nucleus, containing protons and neutrons, that is surrounded by a swarm of orbiting electrons.

For a while many physicists thought that protons, neutrons, and electrons were the Greek "atoms." But in 1968 experimenters at the Stanford Linear Accelerator Center, making use of the increased capacity of technology to probe the microscopic depths of matter, found that protons and neutrons are not fundamental, either. Instead they showed that each consists of three smaller particles called *quarks*—a whimsical name taken from a passage in James Joyce's *Finnegans Wake* by the theoretical physicist Murray Gell-Mann, who previously had surmised their existence. The experimenters confirmed that quarks themselves come in two varieties, which were named, a bit less creatively, *up* and *down*. A proton consists of two up-quarks and a down-quark; a neutron consists of two down-quarks and an up-quark.

Everything you see in the terrestrial world and the heavens above appears to be made from combinations of electrons, up-quarks, and down-quarks. No experimental evidence indicates that any of these three particles is built up from something smaller. But a great deal of evidence indicates that the universe itself has additional particulate ingredients. In the mid-1950s, Frederick Reines and Clyde Cowan found conclusive experimental evidence for a fourth kind of fundamental particle called a *neutrino*—a particle whose existence was predicted in the early 1930s by Wolfgang Pauli. Neutrinos proved very difficult to find because they are ghostly particles that only rarely interact with other matter: an average-energy neutrino can easily pass right through many trillion miles of lead without the slightest effect on its motion. This should give you significant relief, because right now as you

read this, billions of neutrinos ejected into space by the sun are passing through your body and the earth as well, as part of their lonely journey through the cosmos. In the late 1930s, another particle called a *muon*—identical to an electron except that a muon is about 200 times heavier—was discovered by physicists studying cosmic rays (showers of particles that bombard earth from outer space). Because there was nothing in the cosmic order, no unsolved puzzle, no tailor-made niche, the necessitated the muon's existence, the Nobel Prize-winning particle physicist Isidor Isaac Rabi greeted the discovery of the muon with a less than enthusiastic "Who ordered that?" Nevertheless there it was. And more was to follow.

Using ever more powerful technology, physicists have continued to slam bits of matter together with ever increasing energy, momentarily recreating conditions unseen since the big bang. In the debris they have searched for new fundamental ingredients to add to the growing list of particles. Here is what they have found: four more quarks—*charm*, *strange*, *bottom*, and *top*—and another even heavier cousin of the electron, called a *tau*, as well as two other particles with properties similar to the neutrino (called the *muon-neutrino* and *tau-neutrino* to distinguish them from the original neutrino now called the *electron-neutrino*). These particles are produced through high-energy collisions and exist only ephemerally; they are not constituents of anything we typically encounter. But even this is not quite the end of the story. Each of these particles has an *antiparticle* partner—a particle with identical mass but opposite in certain other respects such as its electric charge (as well as its charge with respect to other forces discussed below). For instance, the antiparticle of an electron is called a *positron*—it has exactly the same mass as an electron, but its electric charge is +1 whereas the electric charge of the electron is -1. When in contact, matter and antimatter can annihilate one another and produce pure energy—that's why there is extremely little naturally occurring antimatter in the world around us.

Physicists have recognized a pattern among these particles, displayed in Table 1.1. The matter particles neatly fall into three groups, which are often called *families*. Each family contains two of the quarks, an electron or one of its cousins, and one of the neutrino species. The corresponding particle types across the three families have identical properties except for their mass, which grows larger in each successive family. The upshot is that physicists have now probed the structure of matter to scales of about a billionth of a billionth of a meter and shown that *everything* encountered to date—whether it occurs naturally or is produced artificially with giant atom-smashers—consists of some combination of particles from these three families and their antimatter partners.

A glance at Table 1.1 will no doubt leave you with an even stronger sense of Rabi's bewilderment at the discovery of the muon. The arrangement into families at least gives some semblance of order, but innumerable "whys" leap to the fore. Why are there so many fundamental particles, especially when it seems that the great majority of things in the world around us need only electrons, up-quarks, and down-quarks? Why are there three families? Why not one family or four families or any other number? Why do the particles have a seemingly random spread of masses—why, for in-

stance, does the tau weigh about 3,520 times as much as an electron? Why does the top quark weigh about 40,200 times as much as an up-quark? These are such strange, seemingly random numbers. Did they occur by chance, by some divine choice, or is there a comprehensible scientific explanation for these fundamental features of our universe?

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