VINTAGE

THE ELEGANT UNIVERSE

BRIAN GREENE

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About the Author

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THE ELEGANT UNIVERSE

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

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

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 undertakings, 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 radically 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 Drell, Michael Duff, Kurt Gottfried, Joshua Greene, Teddy Jefferson, Marc Kamionkowski, Yakov Kanter, Andras Kovacs, David Lee, Megan McEwen, Nari Mistry, Hasan Padamsee, Ronen Plesser, Massimo Poratti, 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, Vicky Carstens, David Cassel, Anne Coyle, Michael Duncan, Jane Forman, Wendy Greene, Susan Greene, 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 Von der 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, 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 I 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.

Part I

The Edge of Knowledge

Chapter 1

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 stately 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 resolution 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 to 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 folded 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 them *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 Greeks’ “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 *Finnegan’s 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, that 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 of identical mass but opposite in certain other respects such as its electric charge (as well as its charges 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 to 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 instance, 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 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?

Family 1		Family 2		Family 3	
Particle	***Mass***	***Particle***	***Mass***	***Particle***	***Mass***
Electron	.00054	Muon	.11	Tau	1.9
Electron-neutrino	$< 10^{-8}$	Muon-neutrino	< .0003	Tau-neutrino	< .033
Up-quark	.0047	Charm Quark	1.6	Top Quark	189
Down-quark	.0074	Strange Quark	.16	Bottom Quark	5.2

Table 1.1 The three families of fundamental particles and their masses (in multiples of the proton mass). The values of the neutrino masses have so far eluded experimental determination.

The Forces, or, Where's the Photon?

Things only become more complicated when we consider the forces of nature. The world around us is replete with means of exerting influence: balls can be hit with bats, bungee enthusiasts can throw themselves earthward from high platforms, magnets can keep superfast trains suspended just above metallic tracks, Geiger counters can tick in response to radioactive material, nuclear bombs can

explode. We can influence objects by vigorously pushing, pulling, or shaking them; by hurling or firing other objects into them; by stretching, twisting, or crushing them; or by freezing, heating, or burning them. During the past hundred years physicists have accumulated mounting evidence that all of these interactions between various objects and materials, as well as any of the millions upon millions of others encountered daily, can be reduced to combinations of four fundamental forces. One of these is the *gravitational force*. The other three are the *electromagnetic force*, the *weak force*, and the *strong force*.

Gravity is the most familiar of the forces, being responsible for keeping us in orbit around the sun as well as for keeping our feet firmly planted on earth. The mass of an object measures how much gravitational force it can exert as well as feel. The electromagnetic force is the next most familiar of the four. It is the force driving all of the conveniences of modern life—lights, computers, TVs, telephones—and underlies the awesome might of lightning storms and the gentle touch of a human hand. Microscopically, the electric charge of a particle plays the same role for the electromagnetic force as mass does for gravity: it determines how strongly the particle can exert as well as respond electromagnetically.

The strong and the weak forces are less familiar because their strength rapidly diminishes over all but subatomic distance scales; they are the nuclear forces. This is why these two forces were discovered only much more recently. The strong force is responsible for keeping quarks “glued” together inside of protons and neutrons and keeping protons and neutrons tightly crammed together inside atomic nuclei. The weak force is best known as the force responsible for the radioactive decay of substances such as uranium and cobalt.

During the past century, physicists have found two features common to all these forces. First, as we will discuss

in Chapter 5, at a microscopic level all the forces have an associated particle that you can think of as being the smallest packet or bundle of the force. If you fire a laser beam—an "electromagnetic ray gun"—you are firing a stream of *photons*, the smallest bundles of the electromagnetic force. Similarly, the smallest constituents of weak and strong force fields are particles called *weak gauge bosons* and *gluons*. (The name *gluon* is particularly descriptive: You can think of gluons as the microscopic ingredient in the strong glue holding atomic nuclei together.) By 1984 experimenters had definitively established the existence and the detailed properties of these three kinds of force particles, recorded in Table 1.2. Physicists believe that the gravitational force also has an associated particle—the graviton—but its existence has yet to be confirmed experimentally.

The second common feature of the forces is that just as mass determines how gravity affects a particle, and electric charge determines how the electromagnetic force affects it, particles are endowed with certain amounts of "strong charge" and "weak charge" that determine how they are affected by the strong and weak forces. (These properties are detailed in the table in the endnotes to this chapter.[1]) But as with particle masses, beyond the fact that experimental physicists have carefully measured these properties, no one has any explanation of *why* our universe is composed of these particular particles, with these particular masses and force charges.

Force	*Force particle*	*Mass*
Strong	Gluon	0
Electromagnetic	Photon	0
Weak	Weak gauge bosons	86, 97
Gravity	Graviton	0

Table 1.2 The four forces of nature, together with their associated force particles and their masses in multiples of the proton mass. (The weak force particles come in varieties with the two possible masses listed. Theoretical studies show that the graviton should be massless.)

Notwithstanding their common features, an examination of the fundamental forces themselves serves only to compound the questions. Why, for instance, are there four fundamental forces? Why not five or three or perhaps only one? Why do the forces have such different properties? Why are the strong and weak forces confined to operate on microscopic scales while gravity and the electromagnetic force have an unlimited range of influence? And why is there such an enormous spread in the intrinsic strength of these forces?

To appreciate this last question, imagine holding an electron in your left hand and another electron in your right hand and bringing these two identical electrically charged particles close together. Their mutual gravitational attraction will favor their getting closer while their electromagnetic repulsion will try to drive them apart. Which is stronger? There is no contest: The electromagnetic repulsion is about a million billion billion billion billion (10^{42}) times stronger! If your right bicep represents the strength of the gravitational force, then your left bicep would have to extend beyond the edge of the known universe to represent the strength of the electromagnetic force. The only reason the electromagnetic force does not completely overwhelm gravity in the world around us is that most things are composed of an equal amount of positive and negative

electric charges whose forces cancel each other out. On the other hand, since gravity is always attractive, there are no analogous cancellations—more stuff means greater gravitational force. But fundamentally speaking, gravity is an extremely feeble force. (This fact accounts for the difficulty in experimentally confirming the existence of the graviton. Searching for the smallest bundle of the feeblest force is quite a challenge.) Experiments also have shown that the strong force is about one hundred times as strong as the electromagnetic force and about one hundred thousand times as strong as the weak force. But where is the rationale—the raison d'être—for our universe having these features?

This is not a question borne of idle philosophizing about why certain details happen to be one way instead of another; the universe would be a vastly different place if the properties of the matter and force particles were even moderately changed. For example, the existence of the stable nuclei forming the hundred or so elements of the periodic table hinges delicately on the ratio between the strengths of the strong and electromagnetic forces. The protons crammed together in atomic nuclei all repel one another electromagnetically; the strong force acting among their constituent quarks, thankfully, overcomes this repulsion and tethers the protons tightly together. But a rather small change in the relative strengths of these two forces would easily disrupt the balance between them, and would cause most atomic nuclei to disintegrate. Furthermore, were the mass of the electron a few times greater than it is, electrons and protons would tend to combine to form neutrons, gobbling up the nuclei of hydrogen (the simplest element in the cosmos, with a nucleus containing a single proton) and, again, disrupting the production of more complex elements. Stars rely upon fusion between stable nuclei and would not form with such alterations to fundamental physics. The strength of the

gravitational force also plays a formative role. The crushing density of matter in a star's central core powers its nuclear furnace and underlies the resulting blaze of starlight. If the strength of the gravitational force were increased, the stellar clump would bind more strongly, causing a significant increase in the rate of nuclear reactions. But just as a brilliant flare exhausts its fuel much faster than a slow-burning candle, an increase in the nuclear reaction rate would cause stars like the sun to burn out far more quickly, having a devastating effect on the formation of life as we know it. On the other hand, were the strength of the gravitational force significantly decreased, matter would not clump together at all, thereby preventing the formation of stars and galaxies.

We could go on, but the idea is clear: the universe is the way it is because the matter and the force particles have the properties they do. But is there a scientific explanation for *why* they have these properties?

String Theory: The Basic Idea

String theory offers a powerful conceptual paradigm in which, for the first time, a framework for answering these questions has emerged. Let's first get the basic idea.

The particles in Table 1.1 are the "letters" of all matter. Just like their linguistic counterparts, they appear to have no further internal substructure. String theory proclaims otherwise. According to string theory, if we could examine these particles with even greater precision—a precision many orders of magnitude beyond our present technological capacity—we would find that each is not pointlike, but instead consists of a tiny one-dimensional *loop*. Like an infinitely thin rubber band, each particle contains a vibrating, oscillating, dancing filament that physicists, lacking Gell-Mann's literary flair, have named a *string*. In

Figure 1.1 we illustrate this essential idea of string theory by starting with an ordinary piece of matter, an apple, and repeatedly magnifying its structure to reveal its ingredients on ever smaller scales. String theory adds the new microscopic layer of a vibrating loop to the previously known progression from atoms through protons, neutrons, electrons and quarks.[2]

Although it is by no means obvious, we will see in Chapter 6 that this simple replacement of point-particle material constituents with strings resolves the incompatibility between quantum mechanics and general relativity. String theory thereby unravels the central Gordian knot of contemporary theoretical physics. This is a tremendous achievement, but it is only part of the reason string theory has generated such excitement.

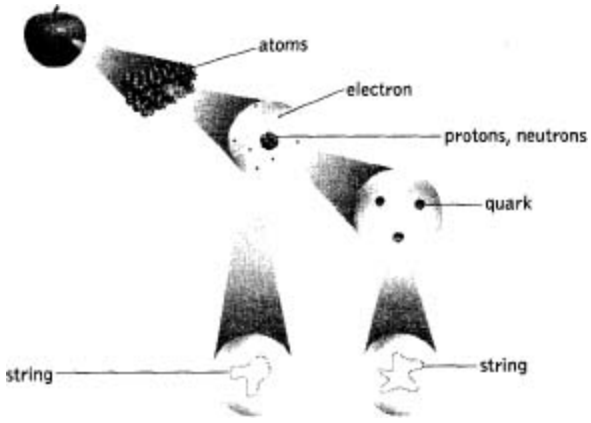

Figure 1.1 Matter is composed of atoms, which in turn are made from quarks and electrons. According to string theory, all such particles are actually tiny loops of vibrating string.

String Theory as the Unified Theory of Everything

In Einstein's day, the strong and the weak forces had not yet been discovered, but he found the existence of even two distinct forces—gravity and electromagnetism—deeply troubling. Einstein did not accept that nature is founded on

such an extravagant design. This launched his thirty-year voyage in search of the so-called *unified field theory* that he hoped would show that these two forces are really manifestations of one grand underlying principle. This quixotic quest isolated Einstein from the mainstream of physics, which, understandably, was far more excited about delving into the newly emerging framework of quantum mechanics. He wrote to a friend in the early 1940s, “I have become a lonely old chap who is mainly known because he doesn’t wear socks and who is exhibited as a curiosity on special occasions.”[3]

Einstein was simply ahead of his time. More than half a century later, his dream of a unified theory has become the Holy Grail of modern physics. And a sizeable part of the physics and mathematics community is becoming increasingly convinced that string theory may provide the answer. From one principle—that everything at its most microscopic level consists of combinations of vibrating strands—string theory provides a single explanatory framework capable of encompassing all forces and all matter.

String theory proclaims, for instance, that the observed particle properties, the data summarized in Tables 1.1 and 1.2, are a reflection of the various ways in which a string can vibrate. Just as the strings on a violin or on a piano have resonant frequencies at which they prefer to vibrate—patterns that our ears sense as various musical notes and their higher harmonics—the same holds true for the loops of string theory. But we will see that, rather than producing musical notes, each of the preferred patterns of vibration of a string in string theory appears as a particle whose mass and force charges are determined by the string’s oscillatory pattern. The electron is a string vibrating one way, the up-quark is a string vibrating another way, and so on. Far from being a collection of chaotic experimental facts, particle properties in string theory are the manifestation of one and