Chapter 1

So What Is String Theory Anyway?

In This Chapter

- Knowing that string theory is based on vibrating strings of energy
- Understanding the key elements of string theory
- Hoping to explain the entire universe with string theory
- Studying string theory could be the driving scientific goal of the 21st century

String theory is a work in progress, so trying to pin down exactly what string theory is, or what the fundamental elements are, can be kind of tricky. Regardless, that's exactly what I try to do in this chapter.

In this chapter, you gain a basic understanding of string theory. I outline the key elements of string theory, which provide the foundation for most of this book. I also discuss the possibility that string theory could be the starting point for a "theory of everything," which would define all of our universe's physical laws in one simple (or not so simple) mathematical formula. Finally, I look at the reasons why you should care about string theory.

String Theory: Seeing What Vibrating Strings Can Tell Us about the Universe

String theory is a physics theory that the universe is composed of vibrating filaments of energy, expressed in precise mathematical language. These *strings* of energy represent the most fundamental aspect of nature. The theory also predicts other fundamental objects, called *branes.* All of the matter in our universe consists of the vibrations of these strings (and branes). One important result of string theory is that gravity is a natural consequence of the theory, which is why scientists believe that string theory may hold the answer to possibly uniting gravity with the other forces that affect matter.

Let me reiterate something important: String theory is a *mathematical* theory. It's based on mathematical equations that can be interpreted in certain ways. If you've never studied physics before, this may seem odd, but *all* physical theories are expressed in the language of mathematics. In this book, I avoid the mathematics and try to get to the heart of what the theory is telling us about the physical universe.

At present, no one knows exactly what the final version of string theory will look like. Scientists have some vague notions about the general elements that will exist within the theory, but no one has come up with the final equation that represents all of string theory in our universe, and experiments haven't yet been able to confirm it (though they haven't successfully refuted it, either). Physicists have created simplified versions of the equation, but it doesn't quite describe our universe . . . yet.

Using tiny and huge concepts to create a theory of everything

String theory is a type of high-energy theoretical physics, practiced largely by particle physicists. It's a *quantum field theory* (see the sidebar "What is quantum field theory?") that describes the particles and forces in our universe based on the way that special extra dimensions within the theory are wrapped up into a very small size (a process called *compactification*). This is the power of string theory — to use the fundamental strings, and the way extra dimensions are compactified, to provide a geometric description of all the particles and forces known to modern physics.

Among the forces needed to be described is, of course, gravity. Because string theory is a quantum field theory, this means that string theory would be a quantum theory of gravity, known as *quantum gravity*. The established theory of gravity, general relativity, has a fluid, dynamic space-time, and one aspect of string theory that's still being worked on is getting this sort of a space-time to emerge out of the theory.

The major achievements of string theory are concepts you can't see, unless you know how to interpret the physics equations. String theory uses no experiments that provide new insights, but it has revealed profound mathematical relationships within the equations, which lead physicists to believe that they must be true. These properties and relationships — called by jargon such as various symmetries and dualities, the cancellation of anomalies, and the explanation of black hole entropy — are described in Chapters 10 and 11.

What is quantum field theory?

Physicists use *fields* to describe the things that don't just have a particular position, but exist at every point in space. For example, you can think about the temperature in a room as a field — it may be different near an open window than near a hot stove, and you could imagine measuring the temperature at every single point in the room. A *field theory,* then, is a set of rules that tell you how some field will behave, such as how the temperature in the room changes over time.

In Chapters 7 and 8, you find out about one of the most important achievements of the 20th century: the development of quantum theory. This refers to principles that lead to seemingly bizarre physical phenomena, which nonetheless seem to occur in the subatomic world.

When you combine these two concepts, you get quantum field theory: a field theory that obeys the principles of quantum theory. All modern particle physics is described by quantum field theories.

In recent years, there has been much public controversy over string theory, waged across headlines and the Internet. These issues are addressed in Part V, but they come down to fundamental questions about how science should be pursued. String theorists believe that their methods are sound, while the critics believe that they are, at best, questionable. Time and experimental evidence will tell which side has made the better argument.

A quick look at where string theory has been

The theory was originally developed in 1968 as a theory that attempted to explain the behavior of *hadrons* (such as protons and neutrons, the particles that make up an atomic nucleus) inside particle accelerators. Physicists later realized this theory could also be used to explain some aspects of gravity.

For more than a decade, string theory was abandoned by most physicists, mainly because it required a large number of extra, unseen dimensions. It rose to prominence again in the mid-1980s, when physicists were able to prove it was a mathematically consistent theory.

In the mid-1990s, string theory was updated to become a more complex theory, called *M-theory,* which contains more objects than just strings. These new objects were called *branes,* and they could have anywhere from zero to nine dimensions. The earlier string theories (which now also include branes) were seen as approximations of the more complete M-theory.

REMEMBER

Technically, the modern M-theory is more than the traditional string theory, but the name “string theory” is still often used for M-theory and its various offspring theories. (Even the original superstring theories have been shown to include branes.) My convention in this book is to refer to theories that contain branes, which are variants of M-theory and the original string theories, using the term “string theory.”

Introducing the Key Elements of String Theory

Five key ideas are at the heart of string theory and come up again and again. It’s best for you to become familiar with these key concepts right off the bat:

- String theory predicts that all objects in our universe are composed of vibrating filaments (and membranes) of energy.
- String theory attempts to reconcile general relativity (gravity) with quantum physics.
- String theory provides a way of unifying all the fundamental forces of the universe.
- String theory predicts a new connection (called *supersymmetry*) between two fundamentally different types of particles, bosons and fermions.
- String theory predicts a number of extra (usually unobservable) dimensions to the universe.

I introduce you to the very basics of these ideas in the following sections.

Strings and branes

When the theory was originally developed in the 1970s, the filaments of energy in string theory were considered to be 1-dimensional objects: strings. (*One-dimensional* indicates that a string has only one dimension, length, as opposed to say a square, which has both length and height dimensions.)

These strings came in two forms — closed strings and open strings. An open string has ends that don’t touch each other, while a closed string is a loop with no open end. It was eventually found that these early strings, called Type I strings, could go through five basic types of interactions, as shown in Figure 1-1.

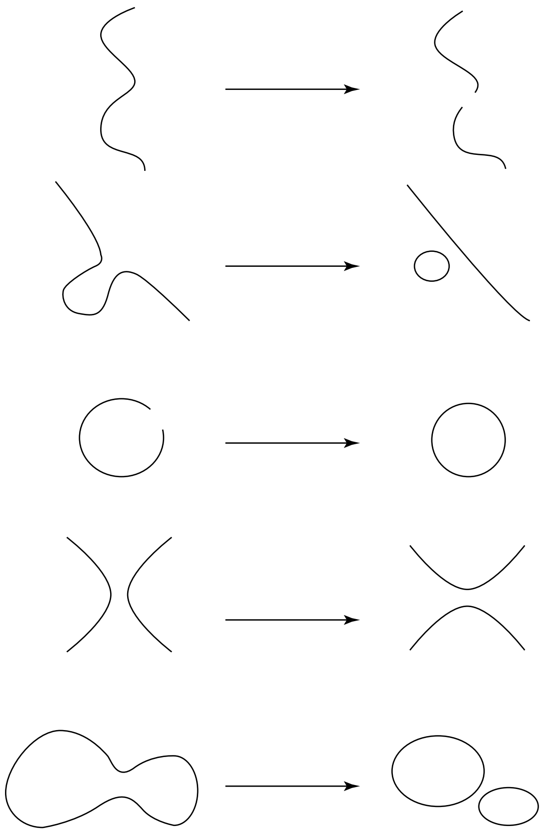

Figure 1-1: Type I strings can go through five fundamental interactions, based on different ways of joining and splitting.

TIP

The interactions are based on a string's ability to have ends join and split apart. Because the ends of open strings can join together to form closed strings, you can't construct a string theory without closed strings.

REMEMBER

This proved to be important, because the closed strings have properties that make physicists believe they might describe gravity! In other words, instead of just being a theory of matter particles, physicists began to realize that string theory may just be able to explain gravity and the behavior of particles.

Over the years, it was discovered that the theory required objects other than just strings. These objects can be seen as sheets, or *branes*. Strings can attach at one or both ends to these branes. A 2-dimensional brane (called a 2-brane) is shown in Figure 1-2. (See Chapter 11 for more about branes.)

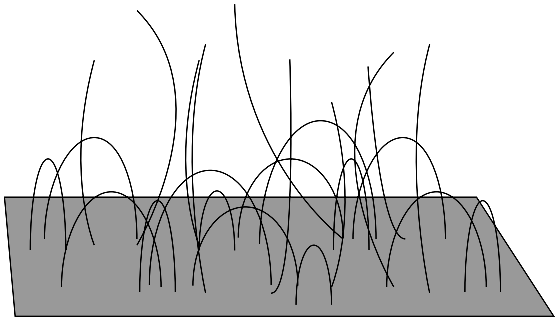

Figure 1-2: In string theory, strings attach themselves to branes.

Quantum gravity

Modern physics has two basic scientific laws: quantum physics and general relativity. These two scientific laws represent radically different fields of study. *Quantum physics* studies the very smallest objects in nature, while *relativity* tends to study nature on the scale of planets, galaxies, and the universe as a whole. (Obviously, gravity affects small particles too, and relativity accounts for this as well.) Theories that attempt to unify the two theories are theories of *quantum gravity,* and the most promising of all such theories today is string theory.

The closed strings of string theory (see the preceding section) correspond to the behavior expected for gravity. Specifically, they have properties that match the long sought-after *graviton,* a particle that would carry the force of gravity between objects.

Quantum gravity is the subject of Chapter 2, where I cover this idea in much greater depth.

Unification of forces

Hand-in-hand with the question of quantum gravity, string theory attempts to unify the four forces in the universe — electromagnetic force, the strong nuclear force, the weak nuclear force, and gravity — together into one unified theory. In our universe, these fundamental forces appear as four different phenomena, but string theorists believe that in the early universe (when there were incredibly high energy levels) these forces are all described by strings interacting with each other. (If you've never heard of some of these forces, don't worry! They're individually discussed in greater detail in Chapter 2 and throughout Part II.)

Supersymmetry

All particles in the universe can be divided into two types: bosons and fermions. (These types of particles are explained in more detail in Chapter 8.) String theory predicts that a type of connection, called *supersymmetry,* exists between these two particle types. Under supersymmetry, a fermion must exist for every boson and a boson for every fermion. Unfortunately, experiments have not yet detected these extra particles.

Supersymmetry is a specific mathematical relationship between certain elements of physics equations. It was discovered outside of string theory, although its incorporation into string theory transformed the theory into supersymmetric string theory (or superstring theory) in the mid-1970s. (See Chapter 10 for more specifics about supersymmetry.)

One benefit of supersymmetry is that it vastly simplifies string theory's equations by allowing certain terms to cancel out. Without supersymmetry, the equations result in physical inconsistencies, such as infinite values and imaginary energy levels.

Because scientists haven't observed the particles predicted by supersymmetry, this is still a theoretical assumption. Many physicists believe that the reason no one has observed the particles is because it takes a lot of energy to generate them. (Energy is related to mass by Einstein's famous $E = mc^2$ equation, so it takes energy to create a particle.) They may have existed in the early universe, but as the universe cooled off and energy spread out after the big bang, these particles would have collapsed into the lower-energy states that we observe today. (We may not think of our current universe as particularly low energy, but compared to the intense heat of the first few moments after the big bang, it certainly is.)

TIP

In other words, the strings vibrating as higher-energy particles lost energy and transformed from one type of particle (one type of vibration) into another, lower-energy type of vibration.

Scientists hope that astronomical observations or experiments with particle accelerators will uncover some of these higher-energy supersymmetric particles, providing support for this prediction of string theory.

Extra dimensions

Another mathematical result of string theory is that the theory only makes sense in a world with more than three space dimensions! (Our universe has three dimensions of space — left/right, up/down, and front/back.) Two possible explanations currently exist for the location of the extra dimensions:

- The extra space dimensions (generally six of them) are curled up (*compactified,* in string theory terminology) to incredibly small sizes, so we never perceive them.
- We are stuck on a 3-dimensional brane, and the extra dimensions extend off of it and are inaccessible to us.

A major area of research among string theorists is on mathematical models of how these extra dimensions could be related to our own. Some of these recent results have predicted that scientists may soon be able to detect these extra dimensions (if they exist) in upcoming experiments, because they may be larger than previously expected. (See Chapter 13 for more about extra dimensions.)

Understanding the Aim of String Theory

To many, the goal of string theory is to be a "theory of everything" — that is, to be the single physical theory that, at the most fundamental level, describes all of physical reality. If successful, string theory could explain many of the fundamental questions about our universe.

Explaining matter and mass

One of the major goals of current string theory research is to construct a solution of string theory that contains the particles that actually exist in our universe.

String theory started out as a theory to explain particles, such as hadrons, as the different higher vibrational modes of a string. In most current formulations of string theory, the matter observed in our universe comes from the lowest-energy vibrations of strings and branes. (The higher-energy vibrations represent more energetic particles that don't currently exist in our universe.)

The mass of these fundamental particles comes from the ways that these string and branes are wrapped in the extra dimensions that are compactified within the theory, in ways that are rather messy and detailed.

For an example, consider a simplified case where the extra dimensions are curled up in the shape of a donut (called a *torus* by mathematicians and physicists), as in Figure 1-3.

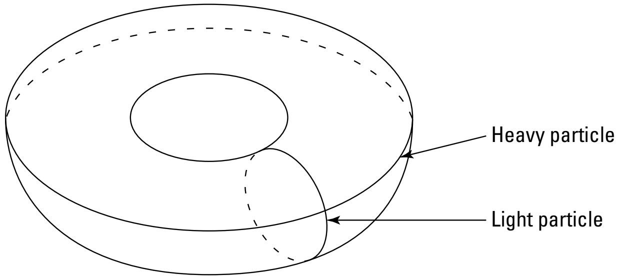

Figure 1-3: Strings wrap around extra dimensions to create particles with different masses.

A string has two ways to wrap once around this shape:

- A short loop around the tube, through the middle of the donut
- A long loop wrapping around the entire length of the donut (like a string wraps around a yo-yo)

TIP

The short loop would be a lighter particle, while the long loop is a heavier particle. As you wrap strings around the torus-shaped compactified dimensions, you get new particles with different masses.

REMEMBER

One of the major reasons that string theory has caught on is that this idea — that length translates into mass — is so straightforward and elegant. The compactified dimensions in string theory are much more elaborate than a simple torus, but they work the same way in principle.

It's even possible (though harder to visualize) for a string to wrap in both directions simultaneously — which would, again, give yet another particle with yet another mass. Branes can also wrap around extra dimensions, creating even more possibilities.

Defining space and time

In many versions of string theory, the extra dimensions of space are compactified into a very tiny size, so they're unobservable to our current technology. Trying to look at space smaller than this compactified size would provide results that don't match our understanding of space-time. (As you see in Chapter 2, the behavior of space-time at these small scales is one of the reasons for a search for quantum gravity.) One of string theory's major obstacles is attempting to figure out how space-time can emerge from the theory.

As a rule, though, string theory is built upon Einstein's notion of space-time (see Chapter 6). Einstein's theory has three space dimensions and one time dimension. String theory predicts a few more space dimensions but doesn't change the fundamental rules of the game all that much, at least at low energies.

REMEMBER

At present, it's unclear whether string theory can make sense of the fundamental nature of space and time any more than Einstein did. In string theory, it's almost as if the space and time dimensions of the universe are a backdrop to the interactions of strings, with no real meaning on their own.

Some proposals have been developed for how this might be addressed, mainly focusing on space-time as an emergent phenomenon — that is, the space-time comes out of the sum total of all the string interactions in a way that hasn't yet been completely worked out within the theory.

However, these approaches don't meet some physicists' definition, leading to criticism of the theory. String theory's largest competitor, loop quantum gravity, uses the quantization of space and time as the starting point of its own theory, as Chapter 18 explains. Some believe that this will ultimately be another approach to the same basic theory.

Quantizing gravity

The major accomplishment of string theory, if it's successful, will be to show that it's a quantum theory of gravity. The current theory of gravity, general relativity, doesn't allow for the results of quantum physics. Because quantum physics places limitations on the behavior of small objects, it creates major inconsistencies when trying to examine the universe at extremely small scales. (See Chapter 7 for more on quantum physics.)

Unifying forces

Currently, four fundamental forces (more precisely called "interactions" among physicists) are known to physics: gravity, electromagnetic force, weak nuclear force, and strong nuclear force. String theory creates a framework in which all four of these interactions were once a part of the same unified force of the universe.

Under this theory, as the early universe cooled off after the big bang, this unified force began to break apart into the different forces we experience today. Experiments at high energies may someday allow us to detect the unification of these forces, although such experiments are well outside of our current realm of technology.

Appreciating the Theory's Amazing (and Controversial) Implications

Although string theory is fascinating in its own right, what may prove to be even more intriguing are the possibilities that result from it. These topics are explored in greater depth throughout the book and are the focus of Parts III and IV.

Landscape of possible theories

One of the most unexpected and disturbing discoveries of string theory is that instead of one single theory, it turns out there may be a huge number of possible theories (or, more precisely, possible solutions to the theory) — possibly as many as 10^{500} different solutions! (That's a 1 followed by 500 zeroes!) While this huge number has prompted a crisis among some string theorists, others have embraced this as a virtue, claiming that this means that string theory is very rich. In order to wrap their minds around so many possible theories, some string theorists have turned toward the *anthropic principle,* which tries to explain properties of our universe as a result of our presence in it. Still others have no problem with this vast number, actually having expected it and, instead of trying to explain it, just trying to measure the solution that applies to our universe.

With such a large number of theories available, the anthropic principle allows a physicist to use the fact that we're here to choose among only those theories that have physical parameters that allow us to be here. In other words, our very presence dictates the choice of physical law — or is it merely that our presence is an observable piece of data, like the speed of light?

REMEMBER

The use of the anthropic principle is one of the most controversial aspects of modern string theory. Even some of the strongest string theory supporters have expressed concern over its application, because of the sordid (and somewhat unscientific) applications to which it has been used in the past and their feeling that all that is needed is an observation of our universe, without anything anthropic applied at all.

As anthropic principle skeptics are quick to point out, physicists only adopt the anthropic principle when they have no other options, and they abandon it if something better comes along. It remains to be seen if string theorists will find another way to maneuver through the string theory landscape. (Chapter 11 has more details about the anthropic principle.)

Parallel universes

Some interpretations of string theory predict that our universe is not the only one. In fact, in the most extreme versions of the theory, an infinite number of other universes exist, some of which contain exact duplicates of our own universe.

As wild as this theory is, it's predicted by current research studying the very nature of the cosmos itself. In fact, parallel universes aren't just predicted by string theory — one view of quantum physics has suggested the theoretical existence of a certain type of parallel universe for more than half a century. In Chapter 15, I explore the scientific concept of parallel universes in greater detail.

Wormholes

Einstein's theory of relativity predicts warped space called a *wormhole* (also called an *Einstein-Rosen bridge*). In this case, two distant regions of space are connected by a shorter wormhole, which gives a shortcut between those two distant regions, as shown in Figure 1-4.

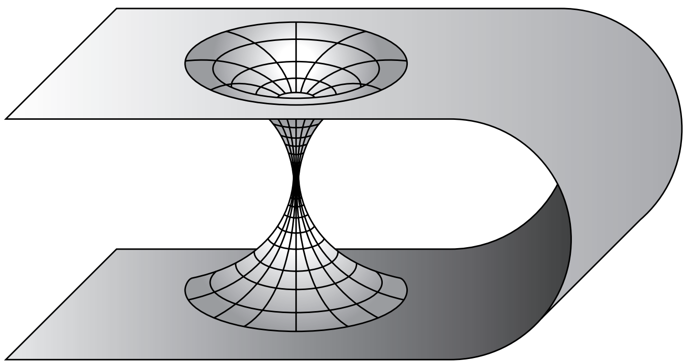

Figure 1-4: Space can warp itself into a wormhole.

String theory allows for the possibility that wormholes extend not only between distant regions of our own universe, but also between distant regions of parallel universes. Perhaps universes that have different physical laws could even be connected by wormholes. (Chapters 15 and 16 contain more info on wormholes.)

In fact, it's not clear whether wormholes will exist within string theory at all. As a quantum gravity theory, it's possible that the general relativity solutions that give rise to potential wormholes might go away.

The universe as a hologram

In the mid-1990s, two physicists came up with an idea called the *holographic principle.* In this theory, if you have a volume of space, you can take all the information contained in that space and show that it corresponds to information "written" on the surface of the space. As odd as it seems, this holographic principle may be key in resolving a major mystery of black holes that has existed for more than 20 years!

Many physicists believe that the holographic principle will be one of the fundamental physical principles that will allow insights into a greater understanding of string theory. (Check out Chapter 11 for more on the holographic principle.)

Time travel

Some physicists believe that string theory may allow for multiple dimensions of time (by no means the dominant view). As our understanding of time grows with string theory, it's possible that scientists may discover new means of traveling through the time dimension or show that such theoretical possibilities are, in fact, impossible, as most physicists believe. (Flip to Chapter 16 if you're ready to make your time travel reservation.)

The big bang

String theory is being applied to cosmology, which means that it may give us insights into the formation of the universe. The exact implications are still being explored, but some believe that string theory supports the current cosmological model of inflation, while others believe it allows for entirely universal creation scenarios.

Inflation theory predicts that, very shortly after the original big bang, the universe began to undergo a period of rapid, exponential inflation. This theory, which applies principles of particle physics to the early universe as a whole, is seen by many as the only way to explain some properties of the early universe.

In string theory, there also exists a possible alternate model to our current big bang model in which two branes collided together and our universe is the result. In this model, called the *ekpyrotic universe,* the universe goes through cycles of creation and destruction, over and over. (Chapter 14 covers the big bang theory and the ekpyrotic universe.)

The end of the universe

The ultimate fate of the universe is a question that physics has long explored, and a final version of string theory may help us ultimately determine the matter density and cosmological constant of the universe. By determining these values, cosmologists will be able to determine whether our universe will ultimately contract in upon itself, ending in a big crunch — and perhaps start all over again. (See Chapter 14 for more on these speculations.)

Why Is String Theory So Important?

String theory yields many fascinating subjects for thought, but you may be wondering about the practical importance of it. For one thing, string theory is the next step in our growing understanding of the universe. If that's not practical enough, then there's this consideration: Your tax money goes to fund scientific research, and the people trying to get that money want to use it to study string theory (or its alternatives).

A completely honest string theorist would be forced to say that there are probably no practical applications for string theory, at least in the foreseeable future. This doesn't look that great on either the cover of a book or a magazine column, so it gets spiced up with talk about parallel universes, extra time dimensions, and discovering new fundamental symmetries of nature. They might exist, but the theory's predictions make it so that they're unlikely to ever be particularly useful, so far as we know.

Understanding the nature of the universe better is a good goal in its own right — as old as humanity, some might say — but when you're looking at funding multibillion dollar particle accelerators or research satellite programs, you might want something tangible for your money and, unfortunately, there's no reason to think that string theory is going to give you anything practical.

Does this mean that exploring string theory isn't important? No, and it's my hope that reading Part II of this book will help illuminate the key at the heart of the search for string theory, or any new scientific truth.

REMEMBER

No one knows where a scientific theory will lead until the theory is developed and tested.

In 1905, when Albert Einstein first presented his famous equation $E = mc^2$, he thought it was an intriguing relationship but had no idea that it would result in something as potent as the atomic bomb. He had no way of knowing the corrections to time calculations demanded by special relativity and general relativity would someday be required to get the worldwide global positioning system (GPS) to operate correctly (as discussed in Chapter 6).

Quantum physics, which on the surface is about as theoretical of a study as they come, is the basis for the laser and transistor, two pieces of technology that are at the heart of modern computers and communication systems.

Even though we don't know what a purely theoretical concept like string theory may lead to, history has shown that it will almost certainly lead somewhere profound.

For an example of the unexpected nature of scientific progress, consider the discovery and study of electricity, which was originally seen as a mere parlor trick. You could predict some technologies from the discovery of electricity, to be sure, such as the light bulb. But some of the most profound discoveries are things that may never have been predicted — radio and television, the computer, the Internet, the cellphone, and so on.

The impact of science extends into culture as well. Another byproduct of electricity is rock and roll music, which was created with the advent of electric guitars and other electric musical instruments.

If electricity can lead to rock and roll and the Internet, then imagine what sort of unpredicted (and potentially unpredictable) cultural and technological advances string theory could lead to!