LEARNING MADE EASY

2nd Edition

String Theory for dummies

A Wiley Brand

Understand the basic concepts of string theory

Learn how strings build on quantum physics and relativity

See the real-world implications of string theory

Andrew Zimmerman Jones
Fell in love with science, and writing about it, 30 years ago

Alessandro Sfondrini
Theoretical physicist by trade, teacher by passion

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2nd edition

by Andrew Zimmerman Jones and
Alessandro Sfondrini

for dummies®
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Contents at a Glance

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Introduction

Why are scientists so excited about string theory? Because string theory is the most likely candidate for a successful theory of quantum gravity — a theory that scientists hope will unite two major physical laws of the universe into one. Right now, these laws (quantum physics and general relativity) describe two totally different types of behavior in totally different ways, and in the realm where neither theory works completely, we really don't know what's going on!

Understanding the implications of string theory means understanding profound aspects of our reality at the most fundamental levels. Is there only one law of nature or infinitely many? Why does our universe follow the laws it does? Is time travel possible? How many dimensions does our universe possess? Physicists are passionately seeking answers to these questions.

Indeed, string theory is a fascinating topic, a scientific revolution that promises to transform our understanding of the universe. As you'll see, these types of revolutions have happened before, and this book helps you understand how physics has developed in the past, as well as how it may develop in the future.

This book contains some ideas that will probably, in the coming years, turn out to be completely false. (We can guarantee this was true about the first edition, and we have no reason to expect it won't also be true of this second edition.) It contains other ideas that may ultimately prove to be fundamental laws of our universe, perhaps forming the foundation for entirely new fields of science and technology. No one knows what the future holds for string theory.

About This Book

In this book, we aim to give a clear understanding of the ever-evolving scientific subfield known as string theory. The media is abuzz with talk about this "theory of everything," and when you're done with this book, you should know what they're talking about (probably better than they do, most of the time).

In writing this book, we've attempted to serve several masters. First and foremost among them has been scientific accuracy, followed closely by entertainment value. Along the way, we've also done our best to use language that you can understand no matter your scientific background, and we've certainly tried to keep any mathematics to a minimum.

We set out to achieve the following goals with this book:

- Provide the information needed to understand string theory (including established physics concepts that predate string theory).
- Establish the successes of string theory so far.
- Lay out the avenues of study that are attempting to gain more evidence for string theory.
- Explore the bizarre (and speculative) implications of string theory.
- Present the critical viewpoints in opposition to string theory, as well as some alternatives that may bear fruit if string theory proves to be false.
- Have some fun along the way.
- Avoid mathematics at all costs. (You're welcome!)

We hope you, good reader, find that we've been successful at meeting these goals.

And while time may flow in only one direction (Or does it? We explore this in Chapter 17), your reading of this book may not. String theory is a complex scientific topic that includes a lot of interconnected concepts, so jumping between concepts isn't quite as easy as it may be in some other *For Dummies* reference books. We've tried to help you out by including quick reminders and providing cross-references to other chapters where necessary. So feel free to wander the pages to your heart's content, knowing that if you get lost, you can work your way back to the information you need.

Foolish Assumptions

About the only assumption we've made in writing this book is that you're reading it because you want to know something about string theory. We've even tried not to assume that you *enjoy* reading physics books. (We do, but we try not to project our own strangeness onto others.)

We have assumed that you have a passing acquaintance with basic physics concepts — maybe you took a physics class in high school or have watched some of the scientific programs about gravity, light waves, black holes, or other physics-related topics on cable channels or your local PBS station. You don't need a degree in physics to follow the explanations in this book, although without a degree in physics you may be amazed that anyone can make sense of any theory so disconnected from our everyday experience. (Even with a physics degree, it can boggle the mind.)

As is customary in string theory books for the general public, the mathematics has been avoided. You need a graduate degree in mathematics or physics to follow the mathematical equations at the heart of string theory, and we've assumed that you don't have either one. Don't worry — while a complete understanding of string theory is rooted firmly in the advanced mathematical concepts of geometry and quantum field theory, we've used a combination of text and figures to explain the fascinating ideas behind string theory.

Icons Used in This Book

Throughout the book, you'll find icons in the margins that are designed to help you navigate the text. Here's what these icons mean:

REMEMBER

Although everything in this book is important, some information is more important than other information. This icon points out information that will definitely be useful later in the book.

TIP

In science, theories are often explained with analogies, thought experiments, or other helpful examples that present complex mathematical concepts in a way that is more intuitively understandable. This icon indicates that one of these examples or hints is being offered.

TECHNICAL STUFF

Sometimes we go into detail that you don't need to know to follow the basic discussion and that's a bit more technical (or mathematical) than you may be interested in. This icon points out that information, which you can skip without losing the thread of the discussion.

Beyond the Book

In addition to what you're reading right now, this book also comes with a free access-anywhere Cheat Sheet. To get it, simply go to `www.dummies.com` and look for String Theory for Dummies Cheat Sheet in the Search box.

If you want to learn more about some of the ideas that laid the basis or string theory, you can also check out *Einstein for Dummies* by Carlos I. Calle.

Where to Go from Here

The *For Dummies* books are organized in such a way that you can surf through any of the chapters and find useful information without having to start at Chapter 1. We (naturally) encourage you to read the whole book, but this structure makes it very easy to start with the topics that interest you the most.

If you have no idea what string theory is, then we recommend looking at Chapter 1 as a starting point, then moving through Chapters 2-3 for a basic overview of what we're talking about. Chapter 4 focuses on laying some foundational ideas about how theoretical science advances. If your physics is rusty, pay close attention to Chapters 5–9, which cover the history and current status of the major physics concepts that pop up over and over again.

If you're familiar with string theory but want some more details, jump straight to Chapters 10 and 11, where we explain how string theory came about and reached its current status. Chapters 12 and 13 go a bit deeper into the specifics, including the recent insights from the holographic principle. Chapter 14 offers some ways of testing the theory, while Chapters 15–17 take concepts from string theory and apply them to some fascinating topics in theoretical physics.

Some of you, however, may want to figure out what all the recent fuss is with people arguing across the blogosphere about string theory. For that, we recommend jumping straight to Chapter 18, which addresses some of the major criticisms of string theory. Chapters 19 and 20 focus heavily on other theories that may either help expand or replace string theory, so they're a good place to go from there.

1

Introducing String Theory

IN THIS PART . . .

Understand the basics of string theory.

Grasp the fundamentals of quantum gravity.

Explore the accomplishments and failures of string theory.

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**

Chapter 1
So What Is String Theory Anyway?

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

In this chapter, you gain a basic understanding of string theory. We outline the key elements of string theory, which provide the foundation for most of this book. We also discuss the possibility that string theory is 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, we 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 models the fundamental particles and interactions in the universe by representing everything in terms of vibrating filaments of energy, called strings. Like all modern physical theories, this image is actually expressed in a precise mathematical language that eventually results in quantitative as well as qualitative predictions.

In this theory, *strings* of energy represent the most fundamental aspect of nature. String theory also predicts other fundamental objects, called *branes*, which emerge as a natural generalization of the strings. All 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.

TIP

We want to 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, we avoid the mathematics and try to get to the heart of what the theory is telling us about the physical universe.

REMEMBER

At present, no one knows exactly what the "final" version of string theory, which will precisely reproduce the universe as we know it, should 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 list of equations 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 a stringy universe, but none quite describes 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 an evolution of *quantum field theory* (see the sidebar "What is quantum field theory?"), which is the current framework that describes the particles and forces in our universe (except gravity). String theory famously predicts that the universe should have more spatial dimensions than the three we observe. It also shows that, in principle, the extra dimensions within the theory can be wrapped up into a very small size (a process called *compactification*) in a way that reproduces fundamental particles like the photon or the electron. This is the power of string theory — using the fundamental strings, and the way extra dimensions are compactified, to provide a unified description of all the particles and forces known to modern physics.

Among the forces that need to be described is, of course, gravity. Superficially, gravity has been the simplest force for humans to grasp since the time of Galileo. There is, however, more than meets the eye, as Einstein discovered: Gravity is a theory of the geometry of space and time. For this reason, it's notoriously hard to marry the ideas of quantum physics with gravity. String theory does incorporate both gravity and quantum physics in a natural way. You can even say that *string theory is a theory of quantum gravity* because it's impossible to construct any string theory without gravity.

Still, not every aspect of gravity is understood from string theory. Importantly, 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 that type of space-time to emerge out of the theory.

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 that nonetheless appear 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.

The major achievements of string theory are concepts you can't see, unless you know how to interpret the physics equations. String theory deals with rather extreme amounts of energy; that's why it's hard to test its predictions directly with experiments. Yet it has revealed profound mathematical relationships within the equations, which leads physicists to believe that they must be true. We discuss these properties and relationships — known by jargon that describes various symmetries and dualities, the cancellation of anomalies, and the explanation of black hole entropy — in Chapters 10 and 11.

In recent years, there has been much public debate over string theory, waged within newsrooms and across the internet. We address these issues in Part 5, 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 they're questionable because they stray too far from contact with experimentation — the true core of physics. Time, and experimental evidence, will tell which side has made the better argument.

A quick look at where string theory has been

String theory was originally developed in 1968 as an attempt 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.) Our 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.

We 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 one-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 Figure 1-1 shows.

TIP

The interactions are based on a string's ability to have its 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. This is a manifestation of the *dualities* of string theory, which you will encounter in Chapter 11 and that resulted in the proposal of M-theory.

REMEMBER

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

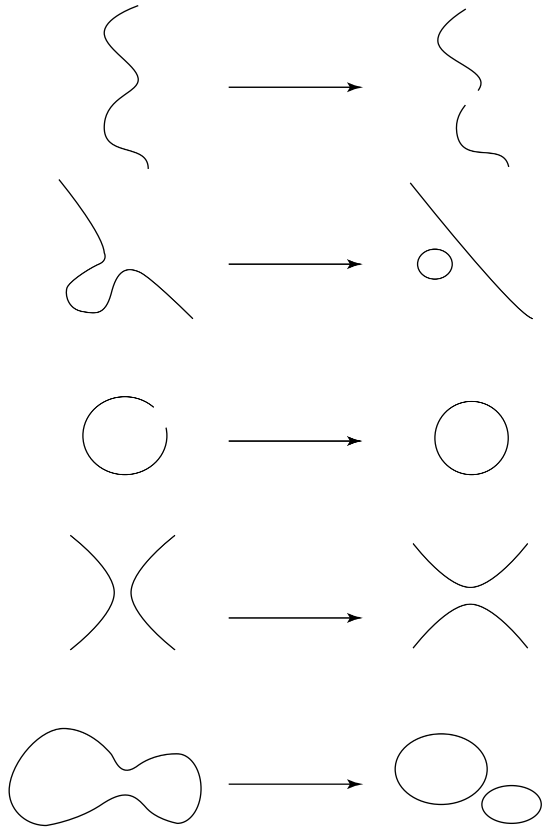

FIGURE 1-1: Type I strings can go through five fundamental interactions, based on different ways of joining and splitting.

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

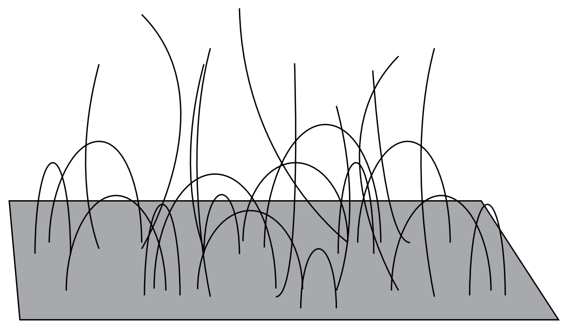

FIGURE 1-2: In string theory, strings attach themselves to branes.

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, but the effect is usually tiny.) Theories that attempt to unify quantum physics and relativity 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 we 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 different types of strings interacting with each other.

That such a unification may be possible isn't entirely surprising to physicists because they discovered 50 years ago that two of the forces are actually one and the same: The electromagnetic force and the weak force can be combined in the "electroweak" force. (If you've never heard of some of these forces, don't worry! We discuss them individually in greater detail in Chapter 2 and throughout Part 2.)

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. (The latest particle that physicists have found is the Higgs boson, which is not one of the supersymmetric partners.)

Supersymmetry is a specific mathematical relationship between certain elements of physics equations. It was discovered outside 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 balances out 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 makes sense only 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 the recent results