INTRODUCTION

String theory is a mystery. It's supposed to be the theory of everything. But it hasn't been verified experimentally. And it's so esoteric. It's all about extra dimensions, quantum fluctuations, and black holes. How can that be the world? Why can't everything be simpler?

String theory is a mystery. Its practitioners (of which I am one) admit they don't understand the theory. But calculation after calculation yields unexpectedly beautiful, connected results. One gets a sense of inevitability from studying string theory. How can this not be the world? How can such deep truths fail to connect to reality?

String theory is a mystery. It draws many talented graduate students away from other fascinating topics, like superconductivity, that already have industrial applications. It attracts media attention like few other fields in science. And it has vociferous detractors who deplore the spread of its influence and dismiss its achievements as unrelated to empirical science.

Briefly, the claim of string theory is that the fundamental objects that make up all matter are not particles, but strings. Strings are like little rubber bands, but very thin and very strong. An electron is supposed to be actually a string, vibrating and rotating on a length scale too small for us to probe even with the most advanced particle accelerators to date. In some versions of string theory, an electron is a closed loop of string. In others, it is a segment of string, with two endpoints.

Let's take a brief tour of the historical development of string theory.

String theory is sometimes described as a theory that was invented backwards. Backwards means that people had pieces of it quite well worked out without understanding the deep meaning of their results. First, in 1968, came a beautiful formula describing how strings bounce off one another. The formula was proposed before anyone realized that strings had anything to do with it. Math is funny that way. Formulas can sometimes be manipulated, checked, and extended without being deeply understood. Deep understanding did follow in this case, though, including the insight that string theory included gravity as described by the theory of general relativity.

In the 1970s and early '80s, string theory teetered on the brink of oblivion. It didn't seem to work for its original purpose, which was the description of nuclear forces. While it incorporated quantum mechanics, it seemed likely to have a subtle inconsistency called an anomaly. An example of an anomaly is that if there were particles similar to neutrinos, but electrically charged, then certain types of gravitational fields could spontaneously create electric charge. That's bad because quantum mechanics needs the universe to maintain a strict balance between negative charges, like electrons, and positive charges, like protons. So it was a big relief when, in 1984, it was shown that string theory was free of anomalies. It was then perceived as a viable candidate to describe the universe.

This apparently technical result started the "first superstring revolution": a period of frantic activity and dramatic advances, which nevertheless fell short of its stated goal, to produce a theory of everything. I was a kid when it got going, and I lived close to the Aspen Center for Physics, a hotbed of activity. I remember people muttering about whether superstring theory might be tested at the Superconducting Super Collider, and I wondered what was so super about it all. Well, superstrings are strings with the special property of supersymmetry. And what might supersymmetry be? I'll try to tell you more clearly later in this book, but for now, let's settle for two very partial statements. First: Supersymmetry relates particles with different spins. The spin of a particle is like the spin of a top, but unlike a top, a particle can never stop spinning. Second: Supersymmetric string theories are the string theories that we understand the best. Whereas non-supersymmetric string theories require 26 dimensions, supersymmetric ones only require ten. Naturally, one has to admit that even ten dimensions is six too many, because we perceive only three of space and one of time. Part of making string theory into a theory of the real world is somehow getting rid of those extra dimensions, or finding some useful role for them.

For the rest of the 1980s, string theorists raced furiously to uncover the theory of everything. But they didn't understand enough about string theory. It turns out that strings are not the whole story. The theory also requires the existence of branes: objects that extend in several dimensions. The simplest brane is a membrane. Like the surface of a drum, a membrane extends in two spatial dimensions. It is a surface that can vibrate. There are also 3-branes, which can fill the three dimensions of space that we experience and vibrate in the additional dimensions that string theory requires. There can also be 4-branes, 5-branes, and so on up to 9-branes. All of this starts to sound like a lot to swallow, but there are solid reasons to believe that you can't make sense of string theory without all these branes included. Some of these reasons have to do with "string dualities." A duality is a relation between two apparently different objects, or two apparently different viewpoints. A simplistic example is a checkerboard. One view is that it's a red board with black squares. Another view is that it's a black board with red squares. Both viewpoints (made suitably precise) provide an adequate description of what a checkerboard looks like. They're different, but related under the interchange of red and black.

The middle 1990s saw a second superstring revolution, based on the emerging understanding of string dualities and the role of branes. Again, efforts were made to parlay this new understanding into a theoretical framework that would qualify as a theory of everything. "Everything" here means all the aspects of fundamental physics we understand and have tested. Gravity is part of fundamental physics. So are electromagnetism and nuclear forces. So are the particles, like electrons, protons, and neutrons, from which all atoms are made. While string theory constructions are known that reproduce the broad outlines of what we know, there are some persistent difficulties in arriving at a fully viable theory. At the same time, the more we learn about string theory, the more we realize we don't know. So it seems like a third superstring revolution is needed. But there hasn't been one yet. Instead, what is happening is that string theorists are trying to make do with their existing level of understanding to make partial statements about what string theory might say about experiments both current and imminent. The most vigorous efforts along these lines aim to connect string theory with high-energy collisions of protons or heavy ions. The connections we hope for will probably hinge on the ideas of supersymmetry, or extra dimensions, or black hole horizons, or maybe all three at once.

Now that we're up to the modern day, let's detour to consider the two types of collisions I just mentioned.

Proton collisions will soon be the main focus of experimental high-energy physics, thanks to a big experimental facility near Geneva called the Large Hadron Collider (LHC). The LHC will accelerate protons in counter-rotating beams and slam them together in head-on collisions near the speed of light. This type of collision is chaotic and uncontrolled. What experimentalists will look for is the rare event where a collision produces an extremely massive, unstable particle. One such particle—still hypothetical—is called the Higgs boson, and it is believed to be responsible for the mass of the electron. Supersymmetry predicts many other particles, and if they are discovered, it would be clear evidence that string theory is on the right track. There is also a remote possibility that proton-proton collisions will produce tiny black holes whose subsequent decay could be observed.

In heavy ion collisions, a gold or lead atom is stripped of all its electrons and whirled around the same machine that carries out proton-proton collisions. When heavy ions collide head-on, it is even more chaotic than a proton-proton collision. It's believed that protons and neutrons melt into their constituent quarks and gluons. The quarks and gluons then form a fluid, which expands, cools, and eventually freezes back into the particles that are then observed by the detectors. This fluid is called the quark-gluon plasma. The connection with string theory hinges on comparing the quark-gluon plasma to a black hole. Strangely, the kind of black hole that could be dual to the quark-gluon plasma is not in the four dimensions of our everyday experience, but in a five-dimensional curved spacetime.

It should be emphasized that string theory's connections to the real world are speculative. Supersymmetry might simply not be there. The quark-gluon plasma produced at the LHC may really not behave much like a five-dimensional black hole. What is exciting is that string theorists are placing their bets, along with theorists of other stripes, and holding their breaths for experimental discoveries that may vindicate or shatter their hopes.

This book builds up to some of the core ideas of modern string theory, including further discussion of its potential applications to collider physics. String theory rests on two foundations: quantum mechanics and the theory of relativity. From those foundations it reaches out in a multitude of directions, and it's hard to do justice to even a small fraction of them. The topics discussed in this book represent a slice across string theory that largely avoids its more mathematical side. The choice of topics also reflects my preferences and prejudices, and probably even the limits of my understanding of the subject.

Another choice I've made in writing this book is to discuss physics but not physicists. That is, I'm going to do my best to tell you what string theory is about, but I'm not going to tell you about the people who figured it all out (although I will say up front that mostly it wasn't me). To illustrate the difficulties of doing a proper job of attributing ideas to people, let's start by asking who figured out relativity. It was Albert Einstein, right? Yes—but if we just stop with that one name, we're missing a lot. Hendrik Lorentz and Henri Poincaré did important work that predated Einstein; Hermann Minkowski introduced a crucially important mathematical framework; David Hilbert independently figured out a key building block of general relativity; and there are several more important early figures like James Clerk Maxwell, George FitzGerald, and Joseph Larmor who deserve mention, as well as later pioneers like John Wheeler and Subrahmanyan Chandrasekhar. The development of quantum mechanics is considerably more intricate, as there is no single figure like Einstein whose contributions tower above all others. Rather, there is a fascinating and heterogeneous group, including Max Planck, Einstein, Ernest Rutherford, Niels Bohr, Louis de Broglie, Werner Heisenberg, Erwin Schrödinger, Paul Dirac, Wolfgang Pauli, Pascual Jordan, and John von Neumann, who contributed in essential ways—and sometimes famously disagreed with one another. It would be an even more ambitious project to properly assign credit for the vast swath of ideas that is string theory. My feeling is that an attempt to do so would actually detract from my primary aim, which is to convey the ideas themselves.

The aim of the first three chapters of this book is to introduce ideas that are crucial to the understanding of string theory, but that are not properly part of it. These ideas—energy, quantum mechanics, and general relativity—are more important (so far) than string theory itself, because we know that they describe the real world. Chapter 4, where I introduce string theory, is thus a step into the unknown. While I attempt in chapters 4, 5, and 6 to make string theory, D-branes, and string dualities seem as reasonable and well motivated as I can, the fact remains that they are unverified as descriptions of the real world. Chapters 7 and 8 are devoted to modern attempts to relate string theory to experiments involving high-energy particle collisions. Supersymmetry, string dualities, and black holes in a fifth dimension all figure in string theorists' attempts to understand what is happening, and what will happen, in particle accelerators.

In various places in this book, I quote numerical values for physical quantities: things like the energy released in nuclear fission or the amount of time dilation experienced by an Olympic sprinter. Part of why I do this is that physics is a quantitative science, where the numerical sizes of things matter. However, to a physicist, what's usually most interesting is the approximate size, or order of magnitude, of a physical quantity. So, for example, I remark that the time dilation experienced by an Olympic sprinter is about a part in 10^{15} even though a more precise estimate, based on a speed of 10 m/s, is a part in 1.8×10^{15}. Readers wishing to see more precise, explicit, and/or extended versions of the calculations I describe in the book can visit this website: http://press.princeton.edu/titles/9133.html.

Where is string theory going? String theory promises to unify gravity and quantum mechanics. It promises to provide a single theory encompassing all the forces of nature. It promises a new understanding of time, space, and additional dimensions as yet undiscovered. It promises to relate ideas as seemingly distant as black holes and the quark-gluon plasma. Truly it is a "promising" theory!

How can string theorists ever deliver on the promise of their field? The fact is, much has been delivered. String theory does provide an elegant chain of reasoning starting with quantum mechanics and ending with general relativity. I'll describe the framework of this reasoning in chapter 4. String theory does provide a provisional picture of how to describe all the forces of nature. I'll outline this picture in chapter 7 and tell you some of the difficulties with making it more precise. And as I'll explain in chapter 8, string theory calculations are already being compared to data from heavy ion collisions.

I don't aim to settle any debates about string theory in this book, but I'll go so far as to say that I think a lot of the disagreement is about points of view. When a noteworthy result comes out of string theory, a proponent of the theory might say, "That was fantastic! But it would be so much better if only we could do thus-and-such." At the same time, a critic might say, "That was pathetic! If only they had done thus-and-such, I might be impressed." In the end, the proponents and the critics (at least, the more serious and informed members of each camp) are not that far apart on matters of substance. Everyone agrees that there are some deep mysteries in fundamental physics. Nearly everyone agrees that string theorists have mounted serious attempts to solve them. And surely it can be agreed that much of string theory's promise has yet to be delivered upon.