types of branes, and where they are located. Unfortunately for the curious, particles and forces confined to distant branes are not required to influence us very strongly. They might merely determine what travels in the bulk, and emit weak signals which might never even reach us. Therefore many conceivable braneworlds will be very difficult to detect, even if they do exist. After all, gravity is the only interaction that we know for sure is shared between the stuff on our brane and the stuff on any other brane, and gravity is an extremely weak force. Without direct evidence, other branes will remain cloistered in the realm of theory and conjecture.

But some of the braneworlds I will present could lead to detectable signals. The detectable braneworlds are the ones that have implications for the physical features of our world. Even though the proliferation of possible braneworlds is in some respects frustrating, it is really quite exciting. Not only might branes help resolve long-standing problems in particle physics, but if we're lucky, and one of the scenarios that I will describe is correct, evidence for braneworlds should appear in experiments with elementary particle physics very soon. We might really be living on a brane—and we might actually know it within a decade.

As of now, we do not know which, if any, of the many possibilities is the true description of the universe. I will therefore keep all options open, so as not to omit anything interesting. Whatever scenario turns out to describe our world, the ones I will present introduce new and fascinating ideas that no one would previously have thought possible.

# 4

# Approaches to Theoretical Physics

She's a model and she's looking good.

Kraftwerk

*"Hey, Athena, is that* Casablanca *you're watching?"*

*"Sure is. Want to join me? This is such a great scene."*

*You must remember this,*
*A kiss is just a kiss.*
*A sigh is just a sigh.*
*The fundamental things apply as time goes by.*

*"Hang on, Ike. Don't you think that last line's a little weird? It's supposed to be so romantic, but it almost sounds as if it's about physics."*

*"Athena, if you think that's strange, you've got to hear the opening verse of the original:"*

*This day and age we're living in*
*Give cause for apprehension,*
*With speed and new invention.*
*And things like fourth dimension,*
*Yet we get a trifle weary*
*With Mr. Einstein's theory . . .*

*"Ike, you don't really expect me to believe that, do you? Next thing I know you'll tell me Rick and Ilsa escape into the seventh dimension! Why don't we forget I ever said anything and just sit back and watch the movie?"*

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now think about string theory and experimentally oriented physics simultaneously. I have continued to follow the model building approach in my research, but I now also incorporate ideas from string theory. I think we're ultimately most likely to make advances by combining the best of both methods.

Albion points out that "the distinction is becoming fuzzy again, catalyzed in large part by the study of extra dimensions. People are talking to each other." The communities are no longer so rigidly defined, and there is more common ground. There has been a renewed convergence of purpose and ideas. Both scientifically and socially, there are now strong overlaps between model builders and string theorists.

One of the beautiful aspects of the extra-dimensional theories I will describe is that ideas from both camps converged to produce them. String theory's extra dimensions might be a nuisance, but they might also prove to be an opportunity for finding new ways of addressing old problems. We can certainly ask where the extra dimensions are, and why we haven't seen them. But we might also ask whether these unseen dimensions could have any import in our world. These dimensions might help explain underlying relationships that are relevant to observed phenomena. Model builders relish the challenge of connecting notions such as extra dimensions to observable quantities such as relations among particle masses. And, if we're lucky, the insights based on extra-dimensional models might successfully address one of the biggest problems facing string theory: its experimental inaccessibility. Model builders have used theoretical elements derived from string theory to attack questions in particle physics. And those models, including the ones that have extra dimensions, will have testable consequences.

When we investigate extra-dimensional models later on, we will see that the model building approach in conjunction with string theory has generated major new insights into particle physics, the evolution of the universe, gravity, and string theory. With the string theorist's knowledge of grammar and the model builder's vocabulary, the two together have begun to write quite a reasonable phrase book.

## *The Heart of Matter*

Ultimately, the ideas we will consider encompass the entire universe. However, these ideas are rooted in particle physics and in string theory—theories that aspire to describe the smallest components of matter. So before setting out on our journey to the extreme theoretical territory these theories address, we'll now take a brief trip into matter down to its smallest parts. On this guided tour of the atom, take note of matter's basic building blocks and the sizes of the objects that different physical theories deal with. They should provide a few landmarks that you can use to orient yourself later on and help you to recognize the components with which each area of physics concerns itself.

The basic premise in most of physics is that elementary particles constitute the building blocks of matter. Peel away the layers, and inside you will always ultimately find elementary particles. Particle physicists study a universe in which these objects are the smallest elements. String theory takes this assumption one step further and postulates that those particles are the oscillations of elementary strings. But even string theorists believe that matter is composed of particles—the unbreakable entities at its core.

It might be difficult to believe that everything is composed of particles; they certainly are not evident to the naked eye. But that is because of the coarse resolving power of our senses, which cannot directly detect anything anywhere nearly as tiny as an atom. Nonetheless, even though we can't directly view them, elementary particles are the elementary building blocks of matter. Just as the images on your computer or TV are composed of tiny dots, even though they present images that appear to be continuous, matter is composed of atoms, which are in turn composed of elementary particles. Physical objects around us appear to be continuous and uniform, but in reality they are not.

Before physicists could look inside matter and deduce its composition, they needed technological advances to create sensitive measuring instruments. But every time they developed more accurate technological tools, *structure*—more elementary constituents—

emerged. And every time physicists had access to tools that could probe still smaller sizes, they discovered yet more fundamental ingredients: *substructure*, constituents of the previously known structural elements.

The goal of particle physics is to discover matter's most basic constituents and the most fundamental physical laws obeyed by those constituents. We study small distance scales because elementary particles interact at these scales, and it's easier to disentangle fundamental forces. At large scales, the basic ingredients are bound into composite objects, which makes fundamental physical laws difficult to disentangle and therefore more obscure. Small distance scales are interesting because new principles and connections apply there.

Matter is not simply a Russian doll with smaller copies of similar entities inside. Smaller distances reveal truly novel phenomena. Even the workings of the human body—the heart and the circulation of the blood, for example—were badly misconstrued until scientists such as William Harvey cut people open in the 1600s and looked inside. Recent experiments have done the same thing with matter, exploring smaller distances where new worlds operate via more fundamental physical laws. And just as the blood's circulation has important consequences for all human activity, the fundamental physical laws have important consequences for us on larger scales.

We now know that all matter is made up of *atoms*, which combine through chemical processes into *molecules*. Atoms are very small, about an angstrom, or one-hundredth of a millionth of a centimeter in size. But atoms are not fundamental: they consist of a central, positively charged *nucleus* which is surrounded by negatively charged *electrons* (see Figure 30). The nucleus is far smaller than the atom, occupying only about one hundred thousandth of the atom's size. And the positively charged nucleus is itself composite: it is made from positively charged *protons* and neutral (uncharged) *neutrons*, collectively known as *nucleons*, which are not very much smaller than the nucleus in size. This was the picture of matter that scientists held before the 1960s, and is very likely the blueprint you learned about in school.

This template for the atom is correct, although, as we will see later, quantum mechanics gives a more interesting picture of an electron's orbits than any picture you can draw. But we now know that even the proton and neutron are not fundamental. Contrary to Gamow's quote in the introduction, the proton and neutron contain substructure, more fundamental ingredients known as *quarks*. The proton contains two *up quarks* and one *down quark*, while the neutron contains two down quarks and one up quark (see Figure 31). These

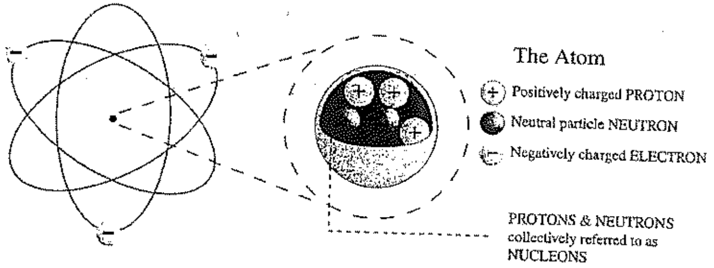


Figure 30. *The atom consists of electrons circulating around a tiny nucleus. The nucleus is composed of positively charged protons and charge-neutral neutrons.*

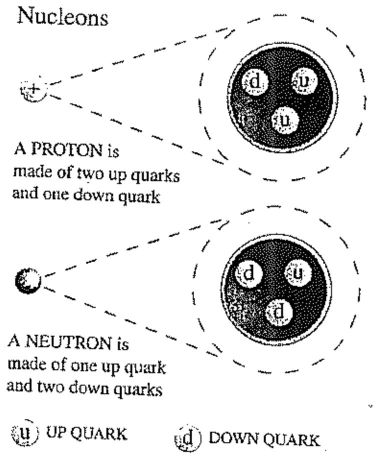


Figure 31. *The proton and neutron are composed of more elementary quarks bound together through the strong force.*

quarks are bound together through a nuclear force known as the *strong force*. The electron, the other component of the atom, is different. So far as we can tell, it is fundamental: the electron cannot be divided into smaller particles and contains no substructure within.

The Nobel Prize-winning physicist Stephen Weinberg coined the term "Standard Model" to label the well-established particle physics theory that describes the interactions of these fundamental building blocks of matter—the electron, the up quark, and the down quark—as well as other fundamental particles that we will get to momentarily. The Standard Model also describes three of the four forces through which the elementary particles interact: electromagnetism, the weak force, and the strong force. (It usually omits gravity.)

Although gravity and electromagnetism were known for hundreds of years, no one understood the last two less familiar forces until the second half of the twentieth century. Those weak and strong forces act on fundamental particles and are important for nuclear processes. They permit quarks to bind together and nuclei to decay, for example.

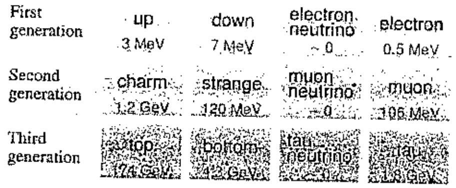
If we wanted, we could also include gravity in the Standard Model. We usually don't though, because gravity is far too weak a force to be of any consequence at the distance scales that are relevant to particle physics at experimentally accessible energies. At very high energies and very small distances, our usual notions about gravity break down; this is relevant to string theory, but it does not happen on measurable distance scales. When studying elementary particles, gravity is important only in certain extensions of the Standard Model, such as the extra-dimensional models we will consider later on. For all other predictions about elementary particles, we can forget about gravity.

Now that we've entered the world of fundamental particles, let's look around a little and take stock of our neighbors. The up quark, the down quark, and the electron lie at the core of matter. However, we now know that there also exist additional, heavier quarks and other heavier electron-like particles that are nowhere to be found in ordinary material.

For example, whereas the electron has a mass of about one-half of one-thousandth that of a proton, a particle called the *muon*, with precisely the same charge as the electron, has a mass that is two hundred times greater than the electron's. A particle called the *tau*, which also has the same charge, has a mass that is ten times greater still. And experiments at high-energy colliders have discovered even heavier particles in the past thirty years. To produce them, physicists needed the large amount of highly concentrated energy that today's high-energy particle colliders can create.

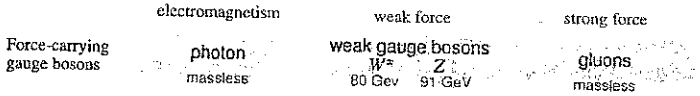
I realize that this section was billed as a tour inside matter, but the particles I am talking about now are not inside the stable objects of the material world. Although all known matter consists of elementary particles, heavier elementary particles are not constituents of matter. You won't find them in your shoelaces, on your table top, or on Mars, or in any other physical object that we know about. But these particles are currently created today at high-energy collider experiments, and they were a part of the early universe immediately after the Big Bang.

Nonetheless, these heavy particles are essential components of the Standard Model. They interact through the same forces as the more familiar particles do, and will very likely play a role in a deeper understanding of matter's most basic physical laws. I've listed the Standard Model particles in Figures 32 and 33. I've included neutrinos and



| | | | | |
|---|---|---|---|---|
| First generation | up<br>3 MeV | down<br>7 MeV | electron neutrino<br>~ 0 | electron<br>0.5 MeV |
| Second generation | charm<br>1.2 GeV | strange<br>120 MeV | muon neutrino<br>~ 0 | muon<br>106 MeV |
| Third generation | top<br>174 GeV | bottom<br>4.2 GeV | tau neutrino<br>~ 0 | tau<br>1.8 GeV |

Figure 32. *The matter particles of the Standard Model and their masses. Particles in the same column have identical charges but different masses.*



| | electromagnetism | weak force | strong force |
|---|---|---|---|
| Force-carrying gauge bosons | photon<br>massless | weak gauge bosons<br>$W^{\pm}$ 80 Gev<br>Z 91 GeV | gluons<br>massless |

Figure 33. *The force-carrying gauge bosons of the Standard Model, their masses, and the forces they communicate.*

force-carrying gauge bosons, which I'll tell you more about in Chapter 7 when I discuss all the elements of the Standard Model in detail.

No one knows why the heavy Standard Model particles exist. The questions of their purpose, what role they play in the ultimate underlying theory, and why their masses are so different from those of the constituents of more familiar matter are some of the major mysteries facing the Standard Model. And these are only a few of the puzzles that the Standard Model leaves unresolved. Why, for example, are there four forces and no others? Could there be others we haven't yet detected? And why is gravity so much weaker than the other known forces?

The Standard Model also leaves open a more theoretical question, the one that string theory hopes to address: how do we reconcile quantum mechanics and gravity consistently at all distance scales? This question differs from the others in that it doesn't concern currently visible phenomena, but is instead a question about the intrinsic limitations of particle physics.

Both types of unanswered question—those that concern visible and purely theoretical phenomena—give us reasons to look beyond the Standard Model. Despite the Standard Model's power and success, we're confident that more fundamental structure awaits discovery and that the search for more fundamental principles will be rewarded. As the composer Steve Reich elegantly put it in the *New York Times* (when making an analogy to a piece he wrote), "First there were just atoms, then there were protons and neutrons, then there were quarks, and now we're talking about string theory. It seems like every 20, 30, 40, 50 years a trapdoor opens and another level of reality opens up."*

Experiments at current and future particle colliders are no longer looking for the ingredients of the Standard Model—those have all been found. The Standard Model nicely organizes these particles according to their interactions, and the full complement of Standard Model particles is now known. Instead, experimenters are looking for particles that should be even more interesting. Current theoretical models include the Standard Model ingredients, but add new elements to address some of the questions that the Standard Model leaves unresolved. We hope that current and future experiments will provide clues that will allow us to distinguish among them and find the true underlying nature of matter.

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*Quoted in Anne Midgette, "At 3 score and 10, the music deepens," *New York Times*, 28 January 2005.

Although we have experimental and theoretical hints about the nature of a more fundamental theory, we are unlikely to know what is the correct description of nature until higher-energy experiments (that probe shorter distances) provide the answer. As we will see later on, theoretical clues tell us that experiments in the next decade will almost certainly discover something new. It probably won't be definitive evidence of string theory, which will be very difficult to discover, but we'll see that it could be something as exotic as new relations in spacetime, or new and as yet unseen extra dimensions—new phenomena that feature in string theory as well as other particle physics theories. And despite the broad scope of our collective imagination, these experiments also have the potential to reveal something that no one has yet thought of. My colleagues and I are very curious about what that will be.

## *Preview*

We know about the structure of matter we just visited as a result of the critical physics developments of the last century. These stupendous advances are essential to any more comprehensive theory of the world we might come up with and were also major achievements in themselves.

Starting in the next chapter, we'll review those developments. Theories grow out of the observations and deficiencies of progenitor theories, and you can better appreciate the role of more recent advances by becoming acquainted with these remarkable earlier developments. Figure 34 indicates some of the ways in which the theories we will discuss interconnect. We'll see how each of these theories was built using the lessons from older ones and how newer theories filled in gaps that were detected only after the older theories were complete.

We'll begin with the two revolutionary ideas of the early twentieth century: relativity and quantum mechanics, through which we learned

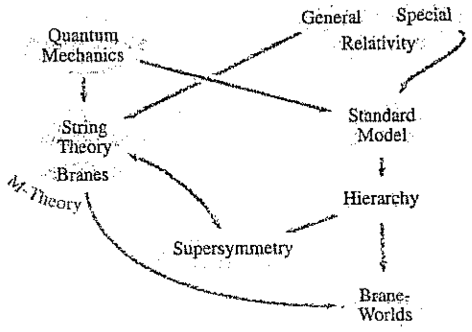

Figure 34. *The fields of physics we will encounter and how they are connected.*

about the shape of the universe and the objects it contains, and the composition and structure of the atom. We'll then introduce the Standard Model of particle physics, which was developed in the 1960s and 1970s to predict the interactions of the elementary particles we just encountered. We'll also consider the most important principles and concepts in particle physics: symmetry, symmetry breaking, and scale dependence of physical quantities, through which we've learned a great deal about how matter's most elementary components create the structures we see.

However, despite its many successes, the Standard Model of particle physics leaves some fundamental questions unanswered—questions so basic that their resolution promises new insight into the building blocks of our world. Chapter 10 presents one of the most interesting and mysterious aspects of the Standard Model: the origin of the elementary particles' masses. We'll see that we almost certainly need a more profound physical theory than the Standard Model if we are to explain the masses of known particles and the weakness of gravity.

Extra-dimensional models address such particle physics problems, but they also use ideas from string theory. After discussing the basics of particle physics, we'll introduce the fundamental motivation and concepts in string theory. We won't derive models directly from string theory, but string theory contains some of the elements that are used when developing extra-dimensional models.

This review covers a lot of ground because research on extra dimensions ties together many theoretical advances in the two major strands of particle physics—model building and string theory. Some familiarity with many of the most interesting recent developments in these fields will help you to better understand the motivations and the methods underlying the development of extra-dimensional models.

However, in case you want to jump around, I will end each of the review chapters with a bulleted list of vital concepts that we will refer to later on when we return to extra-dimensional model building. The bullets will serve as a short cut, a summary, in case you want to skip a chapter or if you want to focus on the material we'll turn to later on. I might occasionally refer to points that aren't in the bullets, but the bullets will review the key ideas that are essential to the major results in the later part of the book.

In Chapter 17 we'll start to explore extra-dimensional braneworlds—theories that propose that the matter of which our universe is composed is confined to a brane. Braneworld ideas have provided new insights into general relativity, particle physics, and string theory. The different braneworlds I'll present make different assumptions and explain different phenomena. I'll summarize the distinctive features of each model with bullets at the end of these chapters as well. We don't yet know which, if any, of these ideas correctly describe nature. But it's entirely conceivable that we'll ultimately discover that branes are a part of the cosmos, and that we—along with other, parallel universes—are confined to them.

One thing I have learned from this research is that the universe often has more imagination than we do. Sometimes its properties are so unexpected that we stumble across them only by accident. Discovering such surprises can be amazing. Our known physical laws turn out to have startling consequences.

Let's now begin our exploration of what those laws are.