20 Introduction

String theory was stumbled on, more or less, by accident. In the late 1960s, string theories were first proposed as theories of the strong interactions. It was quickly realized, however, that, while hadronic physics has a number of string-like features, string theories were not suitable for a detailed description. In their simplest form, string theories have massless spin-2 particles and more than four dimensions of space–time, hardly features of the strong interactions. But a small group of theorists appreciated that the presence of a spin-2 particle implied that these theories were generally covariant and explored them through the 1970s and early 1980s, as possible theories of quantum gravity. Like field theories, the number of possible string theories seemed to be infinite, while, unlike field theories, there was reason to believe that these theories did not suffer from ultraviolet divergences. In the 1980s, however, studies of anomalies in higher dimensions suggested that all string theories with chiral fermions and gauge interactions suffered from quantum anomalies. But in 1984 it was shown that the anomalies cancel for two choices of gauge group. It was quickly recognized that the non-anomalous string theories do come close to unifying gravity and the Standard Model of particle physics. Many questions remained. Beginning in 1995, great progress was made in understanding the deeper structure of these theories. All the known string theories were understood to be different limits of some larger structure. As string theories still provide the only framework in which one can do systematic computations of quantum gravity effects, many workers use the term "string theory" to refer to some underlying structure which unifies quantum mechanics, gravity and gauge interactions.

String theory has provided us with many insights into what a fundamental theory of gravity and gauge interactions might look like, but there is still much we do not understand. We cannot really begin a course of action by enunciating some great principle and seeing what follows. We might, for example, have imagined that the underlying theory would be a string field theory, whose basic objects would create and annihilate strings. Some set of organizing principles would determine the action for this system, and the rest would be a problem of working out the consequences. But there are good reasons to believe that string theory is not like this. Instead, we can at best provide a collection of facts, organized according to the teacher/author/professor's view of the subject at any given moment. As a result, it is perhaps useful first to give at least some historical perspective as to how these facts were accumulated, if only to show that there are, as of yet, no canonical texts or sacred principles in the subject. In the next section we review a little of the remarkable history of string theory. In the following section we will attempt to survey what is known as of the time of writing: the various string theories, with their spectra and interactions, and the connections between them.

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20.1 The peculiar history of string theory

For electrodynamics, the passage from classical to quantum mechanics is reasonably straightforward. But general relativity and quantum mechanics seem fundamentally incompatible. Viewed as a quantum field theory, Einstein's theory of general relativity is a non-renormalizable theory; its four-dimensional coupling constant has dimensions of inverse mass-squared. As a result, quantum corrections are very divergent. From the point of view developed in Part 1, these divergences should be thought of as cut off at some scale associated with new physics: general relativity is an incomplete theory. Hawking has discussed another sense in which gravity and quantum mechanics seem to clash. Hawking's paradox appears to be associated with phenomena at arbitrarily large distances – in particular, with the event horizons of large black holes. Because black holes emit a thermal spectrum of radiation, it seems possible for a pure state – a large black hole – to evolve into a mixed state. Such puzzles suggest that reconciling quantum mechanics and gravity will require a radical rethinking of our understanding of very short-distance physics.

Apart from its potential to reconcile quantum mechanics and general relativity, there is another reason that string theory has attracted so much attention: it is finite and free of the ultraviolet divergences that plague ordinary quantum field theories. In the previous chapters of this book we have adopted the point of view that our theories of nature should be viewed as effective theories; it is not clear that they can be complete in any sense. One might wonder whether some sort of structure exists where the process stops; where some finite, fundamental, theory accounts for the features of our present, more tentative, constructions. Many physicists have speculated through the years that these two questions are related; that an understanding of quantum general relativity would provide a fundamental length scale. The finiteness of string theory suggests it might play this role.

As mentioned above, string theory was discovered by accident in the 1960s, as physicists tried to understand certain regularities of the hadronic S-matrix. In particular, hadronic scattering amplitudes exhibited a feature then referred to as *duality*. Scattering amplitudes with two incoming and two outgoing particles (so-called $2 \rightarrow 2$ processes) could be described equally well by an exchange of mesons in the s channel or in the t channel (but not both simultaneously). This is not a property, at least perturbatively, of conventional quantum field theories. Veneziano succeeded in writing down an expression for an S-matrix with just the required properties. Veneziano's result was extended in a variety of ways and it was soon recognized, by Nambu, Susskind and others, that this model was equivalent to a theory of strings.

One could well imagine coming to string theory by a different route. Quantum field theory describes point particles. Apart from properties like mass and charge, no additional features (size, shape) are assigned to the basic entities. One could well imagine that this is naive but, in describing nature, quantum field theory is extraordinarily successful. In fact, there is no evidence for any size of the electron or the quarks down to distances of order 10^{-17} cm (energy scales of order several TeV). Still, it is natural to try to go

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beyond the idea of particles as points. The simplest possibility is to consider entities with a one-dimensional extent, strings. In the next few chapters we will discuss the features of theories of string. Here we just note that a straightforward analysis yields some remarkable results. A relativistic quantum string theory is necessarily:

1. a theory of general relativity;
2. a theory with gauge interactions;
3. finite; string world sheets are smooth. String interactions do not occur at space–time points but are spread out. As a result, in perturbation theory one does not have the usual ultraviolet divergences of quantum theories of relativistic particles.

These features are not postulated; they are inevitable. Other, seemingly less desirable, features also emerge: the space–time dimension has to be 26 or 10. Many string theories also contain tachyons in their spectrum, whose interpretation is not immediately clear.

As theories of hadronic physics, string theories had only limited success. Their spectra and *S*-matrices did share some features in common with those of the real strong interactions. But, as a result of the features described above – massless particles and unphysical space–time dimensions as well as the presence of tachyons in many cases – strings were quickly eclipsed by QCD as a theory of the strong interactions.

Despite these setbacks, string theory remained an intriguing topic. String theories were recognized to have short-distance behavior very different – and better – from that of quantum field theories. There was reason to think that such theories were free of ultraviolet divergences altogether. Scherk and Schwarz, and also Yoneya, made the bold proposal that string theories might well be sensible theories of quantum gravity. At the time, any concrete realization of this suggestion seemed to face enormous hurdles. The first string theories contained bosons only. But string theories with fermions were soon studied and were discovered to have another remarkable, and until then totally unfamiliar, property: supersymmetry. We have already learned a great deal about supersymmetry, but at this early stage its possible role in nature was completely unclear. In their early formulations, string theories only made sense in special, and at first sight uninteresting, space–time dimensions. But it had been conjectured since the work of Kaluza and Klein that higher-dimensional space-times might be "compactified", leaving theories which appear four-dimensional; Scherk and Schwarz hypothesized that this might be the case for string theories. Over a decade, Green and Schwarz studied supersymmetric string theories further, developing a set of calculational tools in which supersymmetry was manifest and which were suitable for tree level and one-loop computations.Witten and Alvarez-Gaume, however, pointed out that higher-dimensional theories in general suffer from anomalies, which render them inconsistent. They argued that almost all the then-known chiral string theories suffered from just such anomalies. It appeared that the string program was doomed; only two known string theories, theories without gauge interactions, seemed to make sense. Green and Schwarz, however, persisted. By a direct string computation they discovered that, while it was true that almost all would-be string theories with gauge symmetries are inconsistent, there was one exception among the then-known theories, with a gauge group $O(32)$. They reviewed the standard anomaly analysis and realized why $O(32)$ is special; this work raised

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the possibility that there might be one more consistent string theory, based on the gauge group $E_8 \times E_8$. The corresponding string theory, as well as another with gauge group $O(32)$ (known as the heterotic string theories), was promptly constructed.

This work stimulated widespread interest in string theory as a unified theory of all interactions, for now these theories appeared to be not only finite theories of gravity but also nearly unique. Compactification of the heterotic string on six-dimensional manifolds known as Calabi–Yau spaces were quickly shown to lead to theories which at low energies closely resemble the Standard Model, with similar gauge groups, particle content and other features such as repetitive generations, low-energy supersymmetry and dynamical supersymmetry breaking. The various string theories have since been shown to be part of a larger theory, suggesting that one is studying some unique structure which describes quantum gravity. Some basic questions about quantum gravity theories, such as Hawking's puzzle, have been at least partially resolved.

Many questions remain, however. There is still no detailed understanding of how string theory can make contact with experiment. There are a number of reasons for this. String theory, as we will see, is a theory with no dimensionless parameters. This is a promising beginning for a possible unified theory. But it is not clear how a small expansion parameter can actually emerge, allowing systematic computation. String theory provides no simple resolution of the cosmological-constant puzzle. Finally, while there are solutions which resemble nature, there are vastly more which do not. A principle, or dynamics, which might explain the selection of one vacuum or another has not emerged.

Yet string theory is the only model we have for a quantum theory of gravity. More than that, it is the only model we have for a finite theory which could be viewed as some sort of ultimate theory. At the same time, string theory addresses almost all of the deficiencies we have seen in the Standard Model and has the potential to encompass all the solutions we have proposed. The following are some examples.

1. The theory unifies gravity and gauge interactions in a consistent, quantum mechanical, framework.
2. The theory is completely finite. It has no free parameters. The constants of nature must be determined by the dynamics or other features internal to the theory.
3. The theory possesses solutions in which space–time is four-dimensional, with gauge groups close to the Standard Model and repetitive generations. It is in principle possible to compute the parameters of the Standard Model.
4. Many solutions exhibit low-energy supersymmetry, of the sort we have considered in the first part of this book.
5. Other solutions exhibit large dimensions, technicolor-like structures and the like.
6. The theory does not have continuous global symmetries but often possesses discrete symmetries, of the sort we have considered.

While these are certainly encouraging signs, we are a long way from a detailed understanding of how string theory might describe nature. We will see that there are fundamental obstacles to such an understanding. At the same time we will see that string theory provides a useful framework in which to assess proposals for Beyond the Standard Model physics.

The third part of this book is intended to provide the reader with an overview of superstring theory, with a view to connecting string theory with nature. In the next chapter we will study the bosonic string. We will understand how to find the spectra of string theories. We will also understand string interactions. The reason that string theories are so constrained is that strings can only interact in a limited set of ways, essentially by splitting and joining. We will explain how to translate this into concrete computations of scattering amplitudes.

In subsequent chapters we will turn to superstring theories obtain their spectra and understand their interactions. We will then turn to the compactification of string theories, focusing mainly on compactifications to four dimensions. We first consider toroidal compactifications of strings, whose features can be worked out quite explicitly. We also discuss orbifolds, simple string models which can exhibit varying amounts of supersymmetry. Then we devote a great deal of attention to compactifications on Calabi–Yau spaces. These are smooth spaces; superstring theories compactified on these spaces exhibit varying amounts of supersymmetry. Many look quite close to the real world.

Finally, we will turn to the question of developing a realistic string phenomenology. Having seen the many intriguing features of string models, we will point out some of the challenges. Among these are the following.

1. There is a proliferation of classes of string vacua.
2. Within different classes, moduli exist.
3. Mechanisms which generate potentials for moduli are known but, in regimes where calculations can be performed systematically, they tend not to produce stable minima. The question of supersymmetry breaking is closely related to the question of stabilizing moduli.
4. There are detailed issues, such as proton decay, features of quark and lepton masses and many others.

We will touch on some proposed solutions to these puzzles. Much string model building simply posits that moduli have been fixed in some way and a vacuum with desirable properties has somehow been selected by some (unknown) overarching principle. This is often backed up by calculations which, while not systematic, are at least suggestive that moduli are stabilized. An alternative viewpoint is provided by the *landscape*. This refers to the possibility that the theory possesses a huge array of stable and/or metastable ground states. We have already discussed such a hypothesis in the context of the cosmological-constant problem. It is conceivable that string theory provides a realization of this possibility. In particular, string theories possess various tensor fields which, when compactified, support quantized fluxes. The possible choices of flux vastly increase the possible array of (metastable) string ground states. If one simply accepts that there is such a landscape of states, and that the universe samples ("scans") many of these states in some way, then one is led to think about the distributions of parameters of low-energy physics. This applies not merely to the coupling constants but also to the gauge groups, particle content, scale of supersymmetry breaking and value of the cosmological constant. For better or worse, this is in some sense the ultimate realization of the notions of naturalness which so concerned us in Part 1. The question is: why is the universe we see around us the likely outcome of a distribution of this sort? We will leave it for the readers – and for experiment – to sort out which, if any, of these viewpoints may be correct.

This is not a string theory textbook. The reader will not emerge from these few chapters with the level of technical proficiency in weakly coupled strings provided by Polchinski's text, or with the expertise in Calabi–Yau spaces provided by the book of Green *et al.* (1987). In order to obtain quickly the spectra of various string theories, the following chapters heavily emphasize light cone techniques. While some aspects of the covariant treatment are developed in order to explain the rules for computing the *S*-matrix, many important topics, especially the Polyakov path integral approach and Becchi, Rouet, Stora and Tyutin (BRST) quantization, are given only a cursory treatment. Similarly, the introduction to *D*-brane physics provides some basic tools but does not touch on much of the well-developed machinery of the subject.

Suggested reading

The introduction of the book by Green *et al*. (1987) provides a particularly good overview of the history of string theory and some of its basic structure. The introductory chapter of Polchinski's text (1998) provides a good introduction to more recent developments and a perspective on why strings might be important in the description of nature. The reader who wishes a more thorough grounding in the physics of *D*-branes will want to consult the texts of Polchinski (1998), Johnson (2003) and Becker *et al.* (2007).