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String Theory and the Multiverse

Much of the research in particle physics has been inspired by the quest for a unified, fundamental theory of Nature. The hope is that beneath the plurality of particles and forces, there is a single mathematical law that governs all natural phenomena. A major step towards the unification of forces was the development of the electroweak theory. The electromagnetic and weak nuclear forces are indistinguishable at very high energies, but at energies below 100 GeV the symmetry between the forces is broken and the two interactions become distinct. In the 1970s and 80s physicists used a similar approach to include the strong nuclear force. They postulated a large, "grand unified" symmetry, which encompasses electroweak and strong interactions and gets broken at very high energies ~10^{16} GeV. Grand unification is a very attractive idea, and many physicists believe that it will survive as part of the final theory. However, it suffers from significant shortcomings. First, there is a large (in fact, infinite) number of possible grand unified symmetries to choose from, and none of these symmetries appears to be a priori preferred. The list of particles included in the theory is also largely arbitrary. Hence, there is a large number of candidate grand unified theories. This is a problem, since one expects the fundamental theory of Nature to be in some sense unique. Moreover, all attempts to include gravity into the grand unification scheme have proved to be unsuccessful. This led physicists to consider a radically new approach—string theory—which we shall now discuss.

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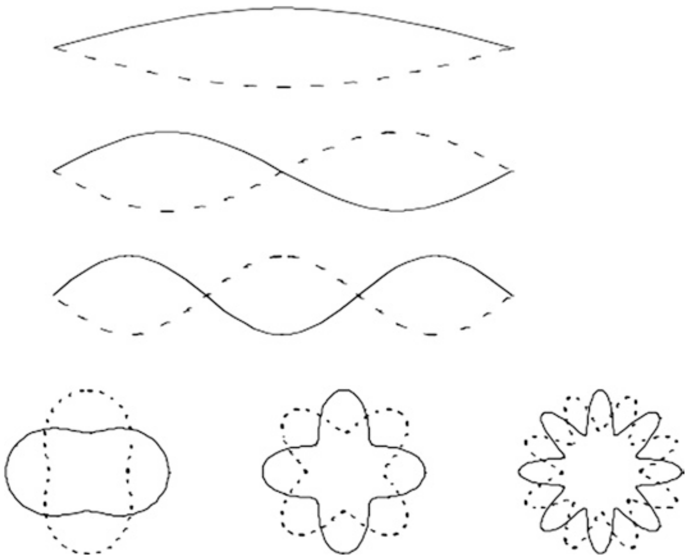

Fig. 19.1 *Top three rows* a violin string, with its two ends fixed, has a multitude of vibration modes. *Bottom row* closed strings can oscillate with different modes giving rise to different particles. Strings can also be open, having two free ends. Here, we only consider closed strings for simplicity

19.1 What Is String Theory?

String theory asserts that the basic building blocks of matter are one-dimensional strings, instead of point-like particles. The strings have high tension, which causes them to vibrate at speeds close to the speed of light. All particles of the Standard Model, like electrons or quarks, and any particles not yet discovered, are postulated to be tiny vibrating strings. They appear to be point-like because the strings are so small.

The properties of a particle—its mass, spin, electric and color charges—are determined by the vibration pattern of the string. While each type of particle is made from the same entity—the string—the many possible vibration patterns give rise to a variety of distinct particles. This is analogous to how a single violin string can generate many different musical notes (see Fig. 19.1). Remarkably, one of the possible string vibration patterns has properties that match the graviton—the quantum of the gravitational field. The graviton plays a role in gravity similar to that of the photon in electromagnetic theory. Thus, the problem of unifying gravity with other interac-

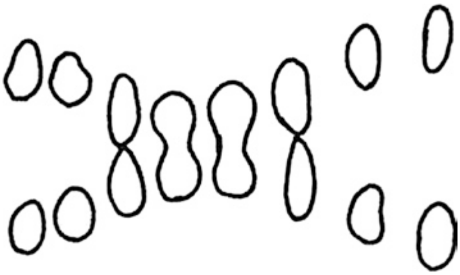

Fig. 19.2 Two strings collide and merge into a single string, which then splits into two again. This corresponds to particle interactions like absorption and re-emission of a photon by an electron

tions does not exist in string theory; in fact, the theory cannot be formulated without gravity.[1]

The typical length of vibrating strings is set by the so-called Planck length,

$$\ell_p = \sqrt{\frac{\hbar G}{c^3}} \sim 10^{-35}\ \mathrm{m} \tag{19.1}$$

which was introduced by Max Planck at the turn of the 20th century, long before the invention of string theory. Planck realized that ℓ_p is the only quantity with dimension of length that can be constructed out of the fundamental constants G, c and $\hbar$. It is also the length scale at which quantum fluctuations of spacetime geometry become important, as we shall discuss in the next chapter. The Planck length is incredibly small: it is 14 orders of magnitude below the smallest length that can be resolved by the most powerful accelerator to date, the Large Hadron Collider. Hence the strings that particles are made of are not likely to be directly observed any time soon.

Particle interactions in string theory can be depicted as strings splitting and joining, as illustrated in Fig. 19.2. One of the major attractions of the theory is that it is free from the problem of infinities that had plagued all earlier attempts to develop a quantum theory of gravity. The problem can be traced to the point-like nature of particles. When two particles collide, their

[1]String theory has a peculiar history. It was first introduced in 1970 as a theory of strong interactions. However, the theory predicted the existence of a massless boson, which had no counterpart among the strongly interacting particles. So string theory was all but discarded, only to be revived several years later, when John Schwartz and Joel Scherk realized that the problematic boson had all the properties of the graviton.

energy is concentrated at a point, so the energy density and the curvature of spacetime become infinite at the time of collision. As a result, calculations of probabilities for various particle interactions often give nonsensical infinite answers. Strings, on the other hand, have a finite size, and string theory gives reasonable, finite results for all probabilities.

19.2 Extra Dimensions

The attractive features of string theory did not come without a cost. Back in the 1970s physicists discovered that the theory suffers from peculiar mathematical flaws, called *anomalies*, that lead to violations of energy conservation and other unacceptable physical processes. They also found that the strength of anomalies depends on the number of space dimensions and that anomalies completely disappear in a 9-dimensional space. In other words, string theory is mathematically consistent only if space has six extra dimensions in addition to the familiar three.

This sounds embarrassing: why would anyone even consider a theory which is in glaring conflict with reality? Let us stop for a moment to think what having extra space dimensions would feel like. Imagine a flatland—a two-dimensional world whose inhabitants are unaware of the third dimension. A resident of this world who has access to the third dimension would then be able to perform truly magical acts. For example, she would easily escape from any jail. It would also be impossible to hide anything from this person. A locked room or a safe would look just like open rectangles from the vantage point of the third dimension. We are not aware of any such phenomena in our world, so does this mean that extra dimensions do not exist?

Not necessarily. Extra dimensions could be curled up, or, as physicists say, compactified, to a very small size. A long garden hose is a simple example of compactification: it has one large dimension along the hose and another one curled up in a small circle. When viewed from a distance, the hose looks like a one-dimensional line, but close by we can see that its surface is a two-dimensional cylinder. String theory suggests that our universe may be very similar: the compact six dimensions may be as small as the Planck length and therefore nearly impossible to detect. However, the sizes of extra dimensions and the manner in which they are compactified affect the vibrational states of the strings. And the vibrational patterns in turn determine the properties of all particles and forces. Hence, the constants of nature in our 3-dimensional world, such as particle masses and the vacuum energy density, depend on the size and shape of the hidden extra dimensions.

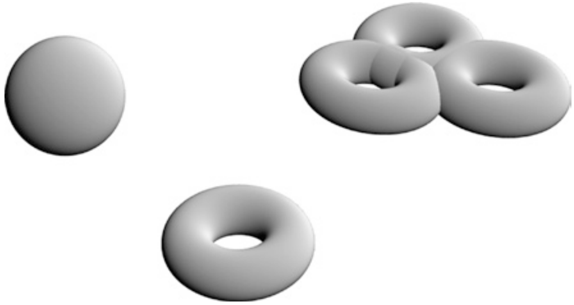

Fig. 19.3 Different ways to compactify two extra dimensions

19.3 The Energy Landscape

If we had only one extra dimension, the only way to compactify it would be to curl it up in a circle. A two-dimensional space can be compactified in a number of different ways: a sphere, a donut, or a shape with two or more "donut holes" (see Fig. 19.3). With more dimensions, the number of possibilities multiplies. Furthermore, there are other ingredients in string theory, called fluxes (these are like magnetic fields), and branes (these are membranes of various dimensionalities), which also add to the number of possible configurations that the hidden dimensions can have.

In order to fully characterize a given configuration, one has to specify the sizes and shapes of extra dimensions, the magnitudes of the fluxes that permeate them, and the locations of the branes that can wrap around them. Altogether, this amounts to specifying $N \sim 500$ different parameters. The role of these parameters in string theory is similar to that of the Higgs fields in particle physics: (i) varying the parameters results in variation of particle properties and (ii) the parameters adjust their values to minimize the potential energy density. In the simple models with one or two parameters, the energy landscape can be visually represented, as illustrated in Figs. 18.9 and 18.11. The energy minima correspond to valleys in the landscape. A similar representation for the energy landscape of string theory would require a space of N dimensions, with one dimension for each of the $N \sim 500$ parameters.

If we try to enumerate the distinct ways the extra-dimensional ingredients can be combined to form a minimum (or "valley") in the energy landscape, we find that there are googols of possibilities. For a very rough estimate, suppose that each of the N parameters can take p different values in the valleys. The total number of possible combinations is then p^N (see Question 6). With $p \sim 10$ and $N \sim 500$, this gives 10^{500}—a truly enormous number! (by comparison, the number of atoms in the observable part of the universe is "only" ~10^{80}).

Each valley in the energy landscape corresponds to a different possible world, with its own particles, interactions and constants of nature. Thus, although strings obey a unique set of laws in higher dimensions, the many compactification choices and extra-dimensional ingredients lead to a huge ensemble of lower-dimensional vacuum states.

This raises many questions. If string theory is correct, then one out of the googols of vacuum states in the landscape corresponds to our world. But which one? How was this particular state selected to be realized in nature? And what about all the states which are not like ours? What kinds of universes do they describe? In some of them gravity may be stronger than the strong nuclear force. Others may have three different kinds of photon, and still others no photons at all. There may be states with more or less than six dimensions compactified, so the number of the remaining large spatial dimensions is different from three. Do these states exist only as possibilities, or could they exist somewhere in the physical spacetime?

19.4 String Theory Multiverse

The hope of string theorists was that the theory would yield a unique vacuum state—presumably ours. They searched for a guiding principle that would select this particular vacuum in the energy landscape. However, no plausible vacuum selection principle has yet been found. Instead, a very different picture has emerged. It was first suggested by Raphael Bousso and Joseph Polchinski, who combined string theory with the ideas of eternal inflation.

Bousso and Polchinski asserted that there are no preferred vacuum states: all vacua should be treated on an equal footing. Suppose the universe begins in a vacuum state corresponding to some valley in the landscape. If the energy density of this vacuum is positive, it will drive exponential inflationary expansion. The initial vacuum is classically stable (as are all vacuum states in the landscape), but sooner or later bubbles of other vacua will begin to nucleate by quantum tunneling through energy barriers to the neighboring valleys. Interiors of positive-energy bubbles will also be inflating and will become sites of further bubble nucleation. In this way, each type of vacuum permitted by the string theory landscape will populate the spacetime. The number of bubbles of all possible types will grow without bound during the course of eternal inflation. The resulting multiverse will look like Fig. 18.10, except that it will include ~10^{500} different kinds of bubble universes, so it would require ~10^{500} colors to depict it!

Most of the string theory practitioners initially viewed this multiverse idea as a giant step backwards. “This is a dangerous idea that I am simply unwilling to contemplate”, wrote the prominent Princeton cosmologist Paul Steinhardt. If the multiverse includes a multitude of different types of bubble universes, how can we ever hope to explain the observed particle properties? Whatever these properties are, we can always expect to find a suitable fit among the googols of vacua in the landscape. This looked very discouraging—a theory that can explain anything may eventually explain nothing at all.

Another approach, advocated by Bousso and Polchinski and by one of the string theory pioneers Leonard Susskind, was to embrace the string multiverse picture and explore where it leads. This approach has been steadily gaining ground among physicists in recent years. If the multiverse picture turns out to be correct, it will have far-reaching consequences for the way in which physicists go about studying the nature of the world, as we will discuss in the next chapter.

19.5 The Fate of Our Universe Revisited

In Chaps. 8 and 9 we addressed the question of the fate of our universe. The discovery of dark energy led us to conclude that the universe will continue to expand faster and faster: distant galaxies will be pushed away from each other with acceleration, but bound systems, like our Galaxy and the Local Group, will remain bound. Although the Milky Way will merge with Andromeda, most of the galaxies that we see today (except those in our Local Group), will eventually be pushed beyond our cosmic horizon. Our descendants will not see a universe filled with hundreds of billions of galaxies, as we do, but rather will find themselves in a lone island galaxy surrounded by almost nothing.

But there is more to the story. If the string landscape picture is correct, then the enormous number of vacuum states must include some positive and some negative energy vacua. This means that our vacuum does not have the lowest possible energy and must be unstable. In other words, we must be living in a false vacuum! Inevitably, a negative-energy bubble will form in our cosmic neighborhood and start to expand, engulfing more and more space. Exactly when this is going to happen is impossible to predict. Bubble nucleation can be extremely slow and can take googols of years. But on the other hand, we cannot exclude the possibility that an expanding negative-energy bubble is charging toward us at this very moment. If so, it will come without a warning: any light the bubble emits will not get to us much ahead of the bubble itself, since it expands at nearly the speed of light. Once it arrives, our world will be completely annihilated, and all objects will be turned into some alien forms of matter.

The stage is now set for the final act of the drama. As we discussed in Chap. 18, negative vacuum energy is gravitationally attractive and will cause the interior of the bubble to contract and eventually collapse to a big crunch. This will be the end of our local region. In the meantime, outside of the crunching bubble inflation will continue and countless new bubbles will be formed. The inflating multiverse will go on forever.

Summary

String theory is perhaps the best candidate we now have for the fundamental theory of nature. It asserts that the basic building blocks of matter are one-dimensional strings. All particles of the Standard Model are thought to be tiny vibrating strings that appear point-like because the strings are so small. Different vibrational patterns give rise to distinct particles.

String theory automatically includes gravity. However, the theory is mathematically consistent only if space has 6 extra dimensions—in addition to the 3 we are familiar with. These extra dimensions are curled up, or compactified, so they are very small and we don't notice them directly. However, the sizes of extra dimensions and the manner in which they are compactified affect the vibrational states of the strings. Hence, properties of our 3-dimensional world, such as particle masses and the vacuum energy density, depend on the size and shape of the hidden dimensions.

It turns out that there are a huge number of different ways to compactify the extra dimensions. Each one corresponds to a different possible world, or vacuum state, with its own particles, interactions and constants of nature. This ensemble of vacuum states is called the string theory landscape.

Combining string theory with the theory of inflation, we arrive at the picture of a multiverse, where bubbles of all possible vacua nucleate and expand, while inflation continues ad infinitum. If this picture is correct, then eventually an expanding bubble of negative vacuum energy will nucleate and engulf our local universe. The negative-energy bubble interior will finally collapse to a big crunch.

Questions

1. Did string theory make any predictions that have been confirmed by experiments? If not, do we have any reasons to believe that string theory is correct?
2. Why is it so difficult to test string theory observationally?

3. String theory is a candidate for a unique physical theory, from which all of physics can be derived. Does this mean that the theory should predict the observed properties of elementary particles?
4. What are some of the most surprising predictions of string theory?
5. Is it possible that there are more than three spatial dimensions in our universe? If so, why don't we see them?
6. If you have 5 different pants in your closet and five different shirts, how many distinct outfits can you make? What if you are then given five different hats—how many pant/top/hat outfits can you now make? If there are 100 extra-dimensional parameters that can each take on one of 2 values, how many possible states can be formed?
7. The string theory landscape provides a vast menu of possible types of vacua. How does the multiverse come to be populated with each and every one of these possible types?
8. What will be the ultimate fate of our observable universe, if the string landscape picture is true? How does this fate differ from the fate of our observable universe if our vacuum is completely stable?