This chapter and the next four build the classical picture of strings. We describe what strings are (in the theory; no one has ever seen a string!). We introduce the different kinds of string, open and closed. We build models to describe their internal motions and their equations of motion. Pay particular attention to the mapping back and forth between spacetime coordinates and the internal parameters measuring the string, and pay attention also to the mass-and-spring wave equations calculating string energy. Here we go!

What strings are made of

We will encounter many objects in string theory, especially strings and branes. Historically strings came first in the development of the theory, and other structures evolved from the strings. We'll concentrate on the strings themselves, for the moment.

Strings are – well, strings. If all the universe is built from strings, we can't dissect a string into component parts.

There are two general types of string, open and closed. Open strings have free ends, which wiggle at enormous velocity (the speed of light). Closed strings are loops, like a rubber band. Strings can interact with each other, sticking together or splitting apart. An open string, for example, can split in two, producing two open strings. Or the ends of an open string can stick together, forming a closed string. All interactions are reversible. The strings are oriented, i.e. they have an associated direction. We can label the ends as different from each other, because of the orientation. Orientation must be preserved in any interaction.

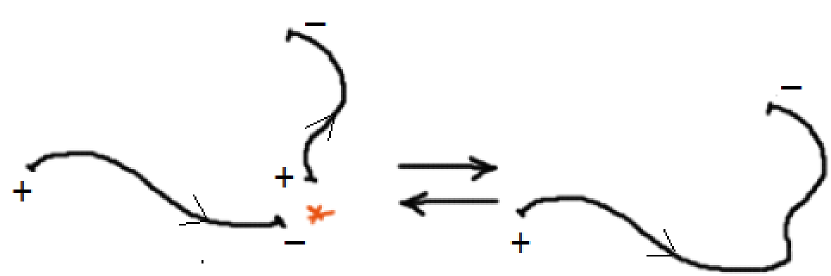

Figure 1.1. Interaction between open strings. Arrows indicate orientation. Anticipating later discussion, ends are labeled as if they carry charge – they do!

By these simple interaction rules, the two ends of an open string can interact to form a closed string, or vice versa. Any theory of open strings, therefore, must also include closed strings.

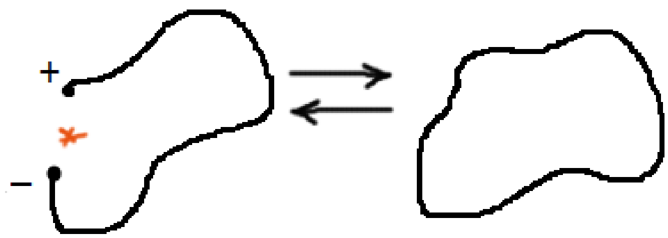

Figure 1.2. Ends of an open string can join to form a closed string. The reverse, splitting, can also occur.

Closed strings, also, are oriented (clockwise or counterclockwise). As with open strings, orientation must be preserved in any interaction, and every interaction is reversible. Two closed strings can "kiss" and form a larger closed string, and a closed string can decompose into an open string (as shown above).

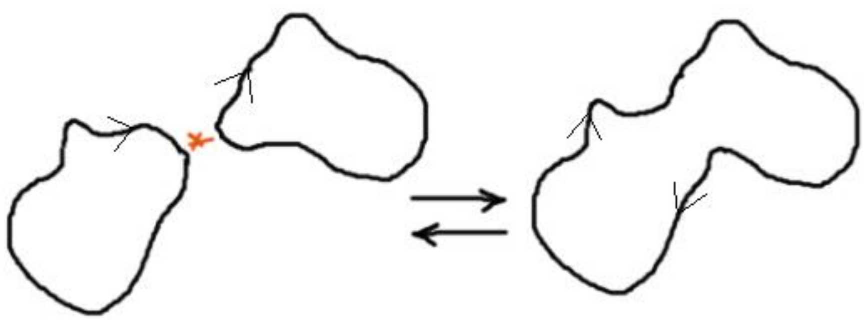

Figure 1.3

How big are they? Tiny, very tiny – on the order 100X the Planck scale. (The Planck length is about $10^{-39}\ cm.$) How massive are they, or, equivalently, how much energy do they carry? String energy is determined by string tension.

That's it; size and orientation and tension. Other properties will help us describe string dynamics, but that's all there is to the physical stuff of strings.

Although the theory builds a universe from strings with no Russian doll component parts, it is convenient to model strings as if they had internal structure. One particularly useful model regards strings as a series of tiny masses connected by springs. These systems are familiar in classical physics, the mathematics is understood, and the model can be quantized.

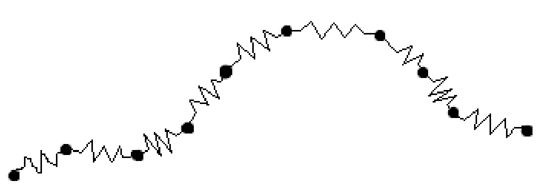

Figure 1.4

Whoa! Wait a minute! We just said that strings have no component parts. Now we've given them springs and masses. What's going on?

Well, we need to describe internal motions within the string. Springs and masses help us do that (but they're not really there). Eventually we'll take the limit in which the masses are infinitesimally close together and recover the real string.

In order to build our string model, we'll need two sets of coordinates. First we need internal coordinates (σ, τ) to represent position σ and "time" τ along the string itself. σ measures position from one end of an open string to the other, or from an arbitrarily selected point around a closed string. For convenience, we set open string length $= \pi$ units of σ, and the circumference of a closed string $= 2\pi$. As we will see, for practical purposes we can usually regard τ same as equivalent to external time, t, but it is rightly an internal parameter and not dependent on any external clock.

Second, we need our familiar (x, t) Cartesian coordinates or, if we're working on a problem with radial symmetry such as spacetime around a black hole, radial coordinates. These are the coordinates in the background across which the strings move. We will describe string motion as the motion of the internal (σ, τ) coordinates against the external (x, t) background.

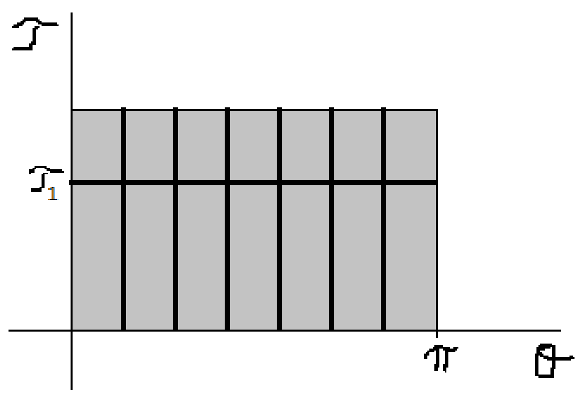

Figure 1.5. World sheet of an open string measured in string parameters σ and τ.

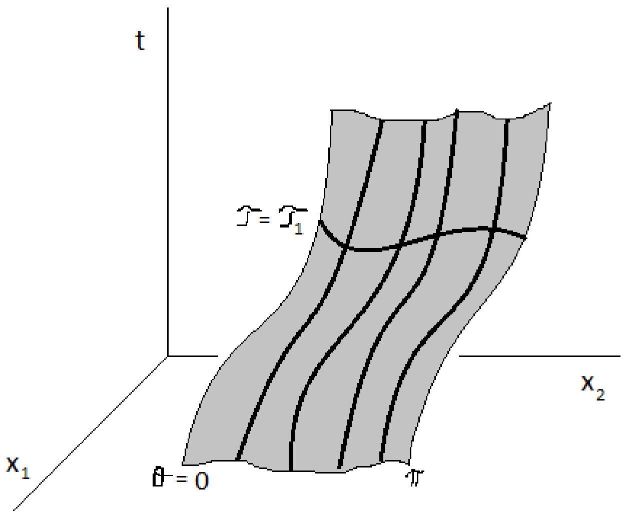

Figure 1.6. World sheet of the same string mapped onto spacetime. Higher spatial dimensions have been suppressed (since we can't display them on the 2d paper).

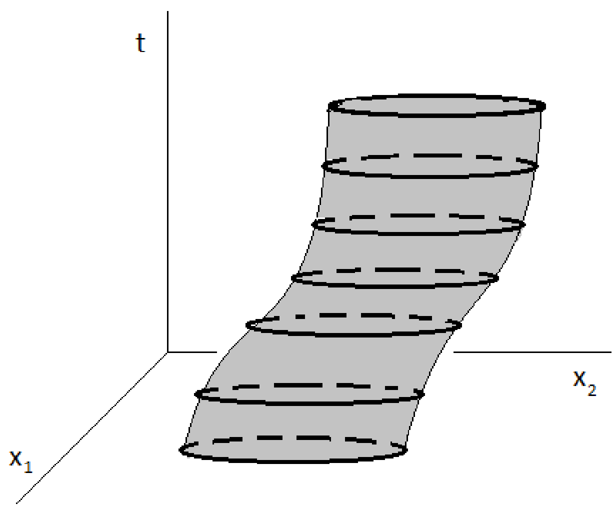

Figure 1.7. World sheet of a closed string showing the loop at successive intervals of time. An actual string would be oscillating internally, so the loops would not be uniformly elliptical as shown.

How do we know all this? How do we know there are open strings and closed strings? How do we know they are oriented? How do we know they interact according to the rules we've described? Well – we don't. We certainly can't see the strings, and they are so tiny we probably never will be able to study them directly (if they exist at all). But we know that if we include these properties in our string model – the mathematics that describe strings – then the model produces particles and phenomena that resemble those in our world. As we shall see, string theory is a self-consistent mathematical edifice, and while it does not yet reproduce precisely the particles and forces of the standard model, it has some remarkable successes to its credit.

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