String Theory

String theory is the name given to several models of fundamental physics whose signature concept is that the elementary particles and force carriers from which the entire universe is assembled consist of minuscule, one-dimensional, vibrating objects—*strings*—rather than the zero-dimensional point particles that provide the basis for the Standard Model of particle physics. The strings are of Planck length, about 10^{-35} m (see Exploring "Natural" Planck Units on page 694 of Chapter 13). Each string vibrates or oscillates at a particular frequency and, like a vibrating violin or guitar string, each string can vibrate in different modes or harmonics, each mode corresponding to a different particle. Thus, the mass of a particle results from how the string is vibrating. Why is the string vibrating in the first place? Because (according to the theories) in the absence of a net external force the string tends to shrink or shorten, that is, decrease its potential energy. However, conservation of energy prevents it from shortening to zero, so it oscillates, sort of like an unloaded real spring displaced from equilibrium oscillates when released. Most of the theories allow both open strings, that is, strings with two distinct ends, and closed strings, that is, strings that are closed loops with the ends joined. Strings can join other strings or divide into additional strings, interpreted as the absorption or emission of particles. There are many additional properties and behaviors of strings, some of which we will refer to below and others whose descriptions we will leave until another time.

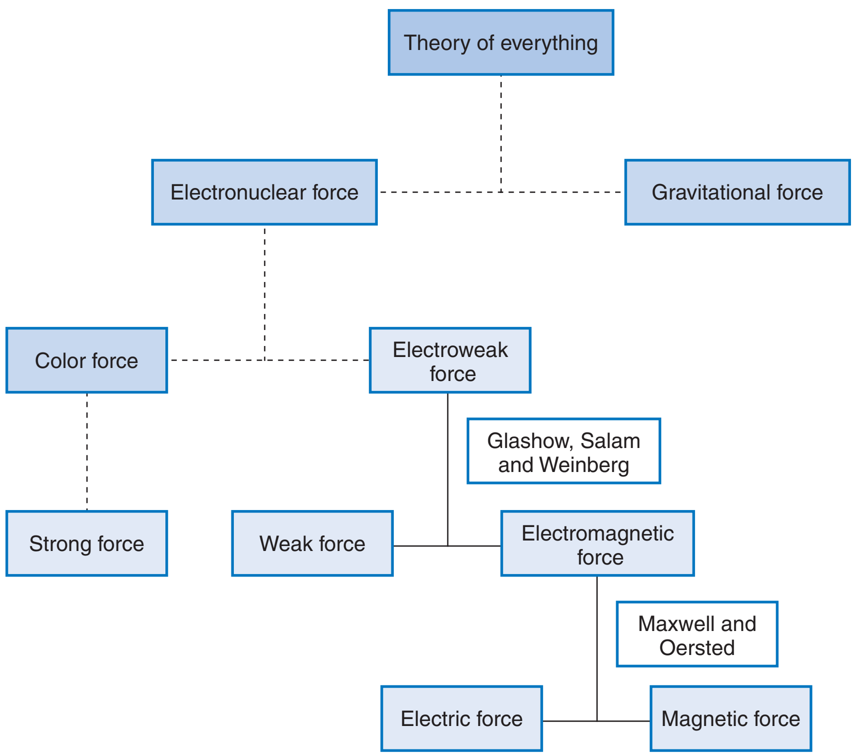
The Promise of Strings

The basic reason that such theories are currently being explored is due to the serious difficulty that arises in combining the two great theories of modern physics—quantum theory and general relativity (i.e., gravitational theory). The realm of quantum theory is normally at the scale of atomic and subatomic dimensions (small regions of spacetime), while that of general relativity is concerned mainly with objects of large mass such as stars and galaxies (large regions of spacetime). If we attempt to describe physics at the Planck scale or below, these two theories yield grossly incompatible views of reality, smooth and flowing from general relativity but random and warped from quantum mechanics.

When point particles are replaced by strings, it appears that this incompatibility problem vanishes (in favor of smooth and flowing) and a consistent theory of *quantum gravity* emerges! String theory also addresses an underlying problem with the Standard Model, which requires the manual insertion of about 20 free parameters and has more than 60 particles in three families that are classed as "fundamental." String theory, on the other hand, requires insertion by hand of only a single free parameter—the length of the string—and may offer some hope of explaining why the particles group themselves into three families. In addition, there is the apparent possibility that the several string theories being developed may be special cases or alternate views of a more general *superstring theory*. One version of the latter is *M theory*, first suggested by Edward Whitten in 1995 but still in its infancy, which combines the five string theories currently being developed by various proponents into a single theory.

Although by no means universally accepted by physicists, these theories are the focus of intense research, another important reason being that they seem to suggest a route to that ultimate goal of a single theory that explains the origins and interrelations between *all* physical phenomena—the hypothetical *Theory of Everything*. Sought unsuccessfully by Einstein, Weyl, Eddington, and many others since their time, the diagram below illustrates the enormous advances in unifying the seemingly disparate basic theories of physics and the huge theoretical challenges that remain. Indeed, many physicists believe that a theory of everything is unattainable.

The Route to the Theory of Everything



Some Problems

The above suggests that string theory may provide the more general replacement for the Standard Model, the long-sought solution for quantum gravity, and the route to the Theory of Everything; however, there are very substantial problems standing in the way of its doing so. Here we describe a few of them very briefly.

Extra Dimensions. All string theories make possible the determination from first principles of the number of spacetime dimensions in the universe. For M theory and the five string theories that are its basis, that number is 10, rather than the 4 we are accustomed to. The origin of the extra dimensions is the requirement for internal consistency of the theory. For example, the energy of the vibration mode of the string that represents the photon determines the photon's mass. That energy includes a contribution from the Casimir effect. The size of that contribution is dependent on the number of dimensions in the universe. Since the photon is observed to be massless, that (along with other related arguments) sets the number of dimensions at 10.

One explanation for why we don't see the extra dimensions is that they are too small to be detected by the means that we currently have available. An often-used analogy is this: think of a garden hose viewed from sufficiently far away that, given the resolution of the eye, appears to be just a line, that is, a one-dimensional string. However, if we move closer, we discover that it has a second dimension, its diameter (or circumference). An insect crawling along its surface can move in two dimensions. Indeed, a gnat flying about inside the hose moves in three dimensions. Thus, in order to see the extra dimensions of string theory, we must get *much* closer to the string. Experimentally, that means we must "look" with particles of extremely short wavelength, that is, wavelengths of the order of the diameter of the string, which means, quantum mechanically, particles of extremely high energy.

Supersymmetry. The string theories all include supersymmetry (SUSY) between matter and forces. This means that the superpartners of the fundamental particles and force carriers listed in Table 12-11 must exist, despite the fact that none have thus far ever been observed. Searches for the SUSY partners is one of the major tasks of the Large Hadron Collider (LHC) at CERN.

Experimental Verification. No version of any of the string theories has at this writing (summer 2011) been experimentally confirmed. String theories thus far have made no experimentally verified predictions that have not already been made by the two major theories of modern physics, quantum theory and general relativity. While string theories necessarily incorporate SUSY, the reverse is not true. SUSY theory does not imply a need for string theory. Therefore, positive results from the LHC search for superpartners would not serve to confirm string theory. In addition, there are versions of string theory that incorporate SUSY only at much higher energies than those available with the LHC, so negative results from those experiments will not serve to negate string theory either.

Other Difficulties. There are other equally formidable problems standing in the path of string theory actually becoming a testable physical theory, which it currently is not. Many of these are mathematical in that string theories as currently formulated are each a series of approximations rather than an exact mathematical structure. Among these is the so-called *landscape* or vacuum structure of the theory. It is far from well understood and in its present form seems to admit as many as 10^{500} distinct forms, each one corresponding to a different universe with different particles, different universal constants, and so on. Clearly, there is much work to be done in string theory and the possibilities are (1) it will turn out to be one of the most remarkable achievements of physics or (2) it will all come to naught. Stay tuned!