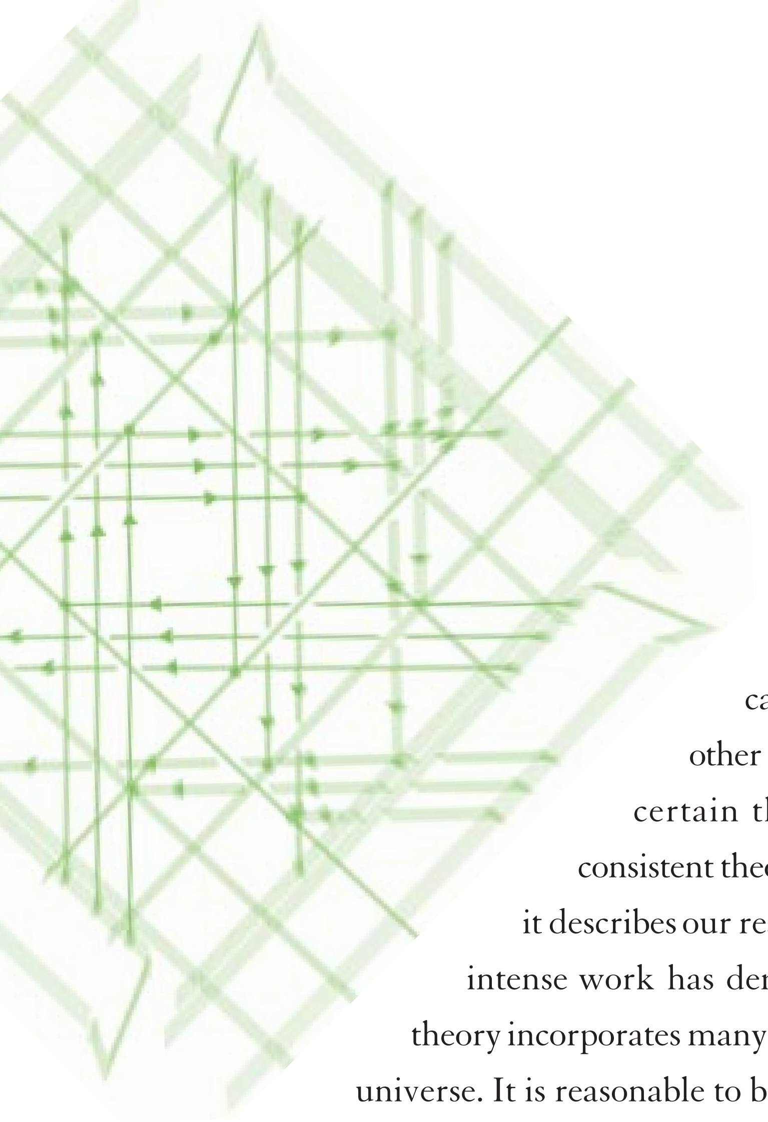
Barton Zwiebach

From Vibrating Strings to a Unified Theory of All Interactions

For the last twenty years, physicists have investigated String Theory rather vigorously. The theory has revealed an unusual depth. As a result, despite much progress in our understanding of its remarkable properties, basic features of the theory remain a mystery. This extended period of activity is, in fact, the second period of activity in string theory. When it was first discovered in the late 1960s, string theory attempted to describe strongly interacting particles. Along came Quantum Chromodynamics—a theory of quarks and gluons—and despite their early promise, strings faded away. This time string theory is a credible candidate for a theory of all interactions—a unified theory of all forces and matter. The greatest complication that frustrated the search for such a unified theory was the incompatibility between two pillars of twentieth century physics: Einstein's General Theory of Relativity and the principles of Quantum Mechanics. String theory appears to be



the long-sought quantum mechanical theory of gravity and other interactions. It is almost certain that string theory is a consistent theory. It is less certain that it describes our real world. Nevertheless, intense work has demonstrated that string theory incorporates many features of the physical universe. It is reasonable to be very optimistic about the prospects of string theory.

Perhaps one of the most impressive features of string theory is the appearance of gravity as one of the fluctuation modes of a closed string. Although it was not discovered exactly in this way, we can describe a logical path that leads to the discovery of gravity in string theory. One considers a string, similar in many ways to the vibrating strings with tension and mass that are studied in freshman physics. This time, however, the string is relativistic. This means that the *classical* mechanics of this string is consistent with Einstein's special theory of relativity. A relativistic string is, in fact, a very interesting and subtle object with a rich spectrum of vibration modes. These classical vibrations, however, cannot be identified with physical particles. But quantum theory comes to the rescue: the quantum mechanics of the relativistic string gives vibration modes that *can* be identified with physical particles! A particular quantum vibration mode of the closed string describes a *graviton*, the quantum of the gravitational field. A particular quantum vibration of an open string describes a *photon*, the quantum of the electromagnetic field. It is the magic of quantization that makes these results possible. In string theory all particles—matter particles and force carriers—arise as quantum fluctuations of the relativistic string. Physicists struggled to invent a quantum theory of gravity during much of the twentieth century, and the answer came from the quantization of classical relativistic strings. We are reminded of an opinion expressed by Dirac in 1966 [1]:

> "The only value of the classical theory is to provide us with hints for getting a quantum theory; the quantum theory is then something that has to stand in its own right. If we were sufficiently clever to be able to think of a good quantum theory straight away, we could manage without classical theory at all. But we're not that clever, and we have to get all the hints that we can to help us in setting up a good quantum theory."

The purpose of this article is to explain some of the unusual features of relativistic strings and to show one way in which string theory may describe the Standard Model of particle physics.

What are relativistic strings?

To gain some understanding of relativistic strings, we can compare them with the more familiar nonrelativistic strings. Nonrelativistic strings are typically characterized by two independent parameters: a string tension T_0 and a mass per unit length μ_0. Each of the four strings on a violin, for example, has a different tension and mass density. When a string with fixed endpoints is also static, the direction along the string is called the *longitudinal direction*. Such a string can exhibit small transverse oscillations (*Figure 1a*). In this case, the velocity of any point on the string is orthogonal to the longitudinal direction. The velocity ν of a transverse *wave* moving along the string is a simple function of the tension and the mass per unit length:

$$\nu = T_0/\mu_0 . \qquad (1)$$

A nonrelativistic string may support a different type of oscillation. When we have a longitudinal oscillation, the velocity of any point on the string remains along the string (*Figure 1b*). In a longitudinal oscillation the wave velocity does not involve the tension, but rather a tension coefficient that describes how the tension changes upon small stretching of the string. More important, a longitudinal wave requires the existence of structure along the string. In order to tell that the various points of the string are really oscillating we must be able to tag them. If this is not possible, a longitudinal oscillation is undetectable because, as a whole, the string does not move. Transverse motion is less subtle; we can always tell when the string moves away from the equilibrium longitudinal direction.

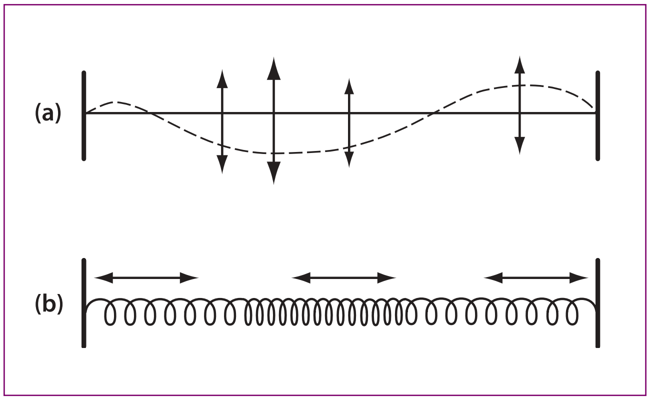


FIGURE 1

(a) In a transverse oscillation the motion of any point on the string is perpendicular to the longitudinal direction. (b) In a longitudinal oscillation the motion of any point on the string (represented by a thin slinky) is along the direction of the string. In order to detect longitudinal motion we must be able to tag the points along the string.

It takes a significant amount of imagination to construct the classical mechanics of relativistic strings. In fact, the mechanics is simplest for the so-called "massless relativistic string." This is the string that one quantizes to obtain string theory. To gain intuition, let's discuss four surprising properties of these strings.

(1) The relativistic string is characterized by its tension T_0 alone—there is no independent mass density parameter. The velocity of transverse waves on

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String Theory for Undergraduates?

The Story Behind 8.251

When, in the fall of 2001, distinguished string theorist Professor Barton Zwiebach first proposed to the Physics Education Committee a new elective for the Department's undergraduate curriculum based upon his upcoming textbook, "A First Course in String Theory," the response was a moment of startled silence. How, the Committee members wondered, could an area of physics be taught to undergraduates that was built upon intellectual concepts viewed as challengingly opaque by not a few of the faculty?

Nevertheless, Zwiebach's talent and reputation as one of the most gifted instructors at MIT was well-established, so the funds were granted to develop the new elective, "8.251: String Theory for Undergraduates." Launched in the Spring 2002 semester and repeated annually, the class continues to attract an equal number of undergraduate and graduate students. It has been so successful that Zwiebach received the 2002 Everett Moore Baker Memorial Award for Excellence in Undergraduate Teaching, the only MIT prize whose winner is chosen solely by undergraduates.

Comments from his students show a keen appreciation of both the topic and the teacher.

"**The class itself was often fantastic.** Midway through the term, when we'd reached Chapter 10 in his book, Prof. Zwiebach announced that we had done three semesters of quantum field theory in one lecture. It was a heady feeling..."

"**I'll always be grateful for 8.251.** Unlike most classes around here, it left a warm and fuzzy spot in my heart. It has had a practical payoff, too: learning to handle commutator relations early gave me a jump over my 8.05 [Quantum Physics II] compadres, and seeing Lagrangian dynamics early let me delve into journal articles with less trepidation. I had a great time with my 8.06 [Quantum Physics III] term paper, mostly because Prof. Zwiebach's class introduced me to fruitful new concepts I could then turn around and apply elsewhere, giving me that spine-tingling shiver of knowledge fitting together."
—Blake C. Stacey (SB '04)

"**Barton Zwiebach's course** finally bridges the gap between theoretical physics as taught on the undergraduate level and its current frontier, string theory. Before taking this course, I was convinced one would need to learn very sophisticated mathematical tools before one could try to understand, even on a basic level, what string theory is about. [Thus] it was very impressive, and intellectually very satisfying, to see from Zwiebach's class that basic knowledge about classical and quantum mechanics is sufficient to get a head start in this subject....To make this theory accessible to students at the undergraduate level can hardly be overestimated in its importance."
—Martin Zwierlein, Graduate Student, Atomic Physics

"**Originally I decided to take the class** because string theory is...on the frontier of physics, and this class proposed to teach me the subject (at least some parts of it) with a minimum of previously required knowledge..."

"**The class itself was a novel way** of teaching the topic and...quite different from the way string theory is taught in other texts. Instead of beginning with abstract field theoretic concepts, 8.251 started rooted in the physics that we were all familiar with: the mechanics of a simple string. It all started there and quickly went through many iterations until arriving at the quantum mechanics of relativistic strings. Though at times the math was difficult, as is unavoidable in this subject, the concepts were very clear throughout the journey, which also included a discussion of the theory of branes, T-duality and a few exotic topics like string thermodynamics and black holes."

"**One thing that is for certain** is that the class would simply not be the same without Prof. Zwiebach; his clear lecturing and willingness (and ability) to answer questions was great. I enjoyed the class to the point of volunteering to help look over the chapters of the textbook that were yet to be written, because I really wanted to see more material on this subject."

"**All in all, the class was very exciting;** it was unlike most other physics classes at MIT and remains among my favorites."
—Alan M. Dunn (SB '04)

For a more detailed look at 8.251: STRING THEORY FOR UNDERGRADUATES, visit the class home page at *http://mit.edu/8.251/www/*. The class textbook, *A First Course in String Theory* [2], is available from Cambridge University Press (*http://publishing.cambridge.org/stm/physics/strings/*).

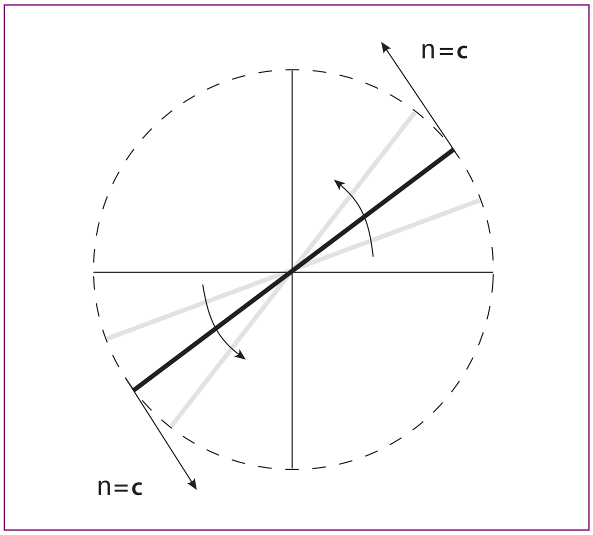

FIGURE 2

A relativistic open string can rotate rigidly about its midpoint. The angular velocity must be such that the endpoints move with the speed of light.

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this string is the velocity of light c, so using (1) the mass density μ_0 is fixed once T_0 is fixed:

$$c = \sqrt{T_0/\mu_0} \;\rightarrow\; \mu_0 = T_0/c^2. \qquad (2)$$

Special relativity tells us that mass and energy are interchangeable, but familiar examples involve quantum processes, such as massive particles that annihilate into energetic (zero-mass) photons. In the relativistic string, energy/mass conversion occurs classically. Imagine beginning with an infinitesimally short relativistic string and stretching it out to some length L. Since the string tension is constant, the work done on the string is equal to the product T_0L of the tension times the length. This energy makes up the rest mass of the string. Energy is converted into rest mass by stretching the string! The mass is equal to the energy divided by c^2, so it equals T_0L/c^2. Consequently, the mass per unit length is T_0/c^2, as anticipated in (2). The relativistic string has no intrinsic mass; the mass arises from work done against the tension.

(2) The relativistic string does not support longitudinal oscillations. This is a revealing fact: it tells us that the string has no substructure. The points along the relativistic string cannot be tagged in an unambiguous way. When a string moves a little, we cannot really tell which point went where. There is a minor exception: if we have an open string, we can keep track of the motion of the endpoints, which, after all, are points. Many times people ask, What is the string made of? The lack of longitudinal oscillations tells us that no meaningful answer can be provided: the classical relativistic string has no constituent parts that can be identified.

(3) The endpoints of a free relativistic open string move with the speed of light. For familiar strings, oscillations require that the motion of the endpoints be constrained. The simplest constraint is to fix the endpoints; the string can then have a nonzero tension and oscillations are possible. Nontrivial motion is possible for relativistic open strings even if the endpoints are not fixed. Elementary mechanics suggests that the effective tension of the string must vanish at the endpoints. This is actually achieved when the endpoints move at the speed of light. One of the simplest open string motions is that of an open string that rotates rigidly about its midpoint (*Figure 2*). This motion has an unusual property: the angular momentum J of this string is linearly proportional to the square of the energy E of the string:

$$J = \alpha' E^2 \qquad (3)$$

The constant of proportionality α' is called the slope parameter. The above property was the reason why physicists attempted (and still attempt!) to use some kind of string theory to describe strongly interacting particles. Indeed, hadronic resonances fit rather accurately a linear relation between angular momentum and the square of the mass (or the square of the energy). This relation is completely unusual: for a rigid bar rotating nonrelativistically about its midpoint, one finds the rather different $J\;;\;=E$. Equation (3) can be understood roughly by assuming that the mass of the string is concentrated at the endpoints. Since the speed of the endpoints is constant and equal to the speed of light, the angular momentum is proportional to the length of the string times the mass of the string. Given that both the length and the mass of the string are proportional to its energy, the angular momentum is proportional to the energy squared.

(4) A relativistic string has an orientation which determines the sign of the string charge. Consider an electron and its antiparticle, the positron. They are oppositely charged point particles. Being zero-size points, there is no intrinsic geometrical property that distinguishes their charges. This is different in string theory. Relativistic strings come with an orientation. For a closed string, the orientation is an arrow that defines a preferred direction along the string. One can travel along a closed string in two directions; the orientation picks one out of these two (*see Figure 3*). It turns out that oppositely oriented strings have opposite *string* charges. In contrast to the case of point particles, in string theory the sign of charge has a geometrical basis. While string charge is a novel concept, the implications for open strings are readily understood. To specify an open string we must choose a direction or draw an arrow along the string. This arrow creates a clear-cut distinction between the two, previously similar, endpoints: the arrow points away from one endpoint, called the beginning endpoint, and towards the other endpoint, called the final endpoint. A surprising effect then takes place: the string charge forces the open string endpoints to acquire opposite *electric* charges! String

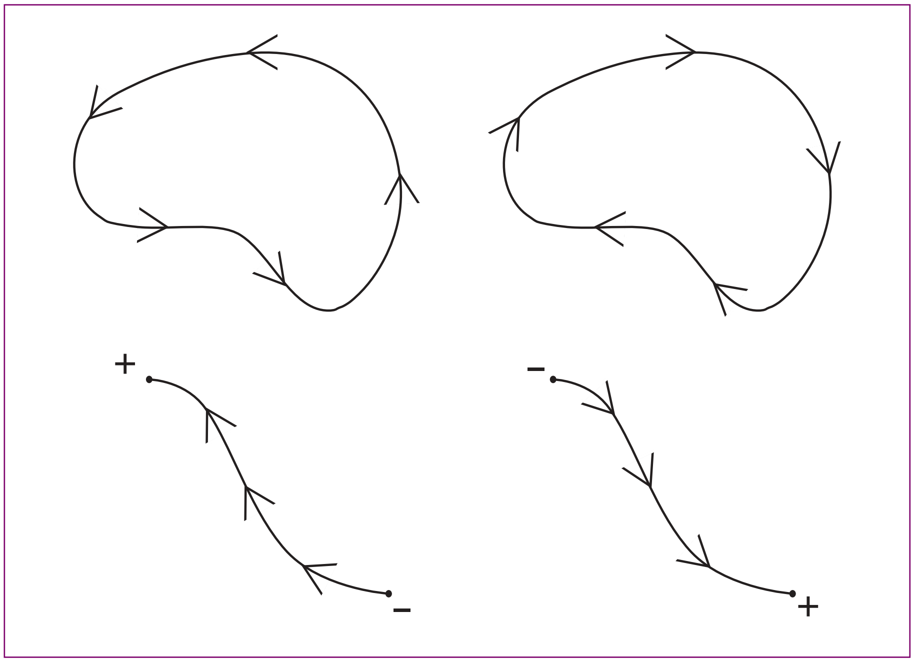


Figure 3

Relativistic strings carry orientation, a direction of travel along the string indicated by arrows. ***Top line:*** *two oppositely oriented closed strings are states with opposite string charge.* ***Bottom line:*** *two oppositely oriented open strings. The endpoints of open strings carry ordinary electric charge. The charges at the open string endpoints are opposite: (+) at the final endpoint and (–) at the beginning endpoint.*

charge transmutes into electric charge. The orientation points from the negatively charged to the positively charged endpoint. Since open strings carry electric charges, we may attempt to identify known charged particles with excitations of open strings.

The above properties, derived in the classical theory of strings, remain true in the quantum theory of strings. Further surprises emerge, however, when relativistic strings are quantized. One finds that quantum mechanical strings cannot propagate consistently in spacetimes of arbitrary dimensionality. For the simplest—bosonic strings—the spacetime must be twenty-six dimensional. For superstrings, strings whose excitations include bosons and fermions, the dimensionality of spacetime is ten, one of time and nine of space. Quantization also implies that strings have quantum states of oscillation. This allows us to identify the oscillations of strings with particles, which are themselves quanta of familiar fields. The masses of the particles associated with string oscillations are computed using the quantum theory. While closed string oscillations that could be identified with gravitons have positive mass in the classical theory, their mass turns out to be exactly zero in the quantum theory! This is precisely what is needed, since gravitons are exactly massless particles. There was no reason to expect gravity to arise from fluctuating strings, but it does. Quantum relativistic strings provide a theory of quantum gravity. A related effect occurs for open strings: massless oscillations of open strings represent photons.

Building blocks of the Standard Model

There are four known forces in nature. The Standard Model of particle physics summarizes the present-day understanding of three of them. It describes the electromagnetic force, the weak force and the strong force, but leaves out the gravitational force. The Standard Model also describes the elementary particles that have been discovered so far.

The electromagnetic force is transmitted by photons, the quanta of the electromagnetic field. The weak force is responsible for the process of nuclear beta decay, in which a neutron decays into a proton, an electron and an anti-neutrino. The strong force or color force holds together the constituents of the neutron, the proton, the pions and many other subnuclear particles. These constituents, called quarks, are held so tightly by the color force that they cannot be seen in isolation.

In the late 1960s the Weinberg-Salam model of *electroweak* interactions put together electromagnetism and the weak force into a consistent, unified framework. The theory is initially formulated with four massless particles that carry the forces. A process of symmetry breaking gives mass to three of these particles: the W^+, the W^-, and the Z^0. These particles are the carriers of the weak force. The particle that remains massless is the photon. The theory of the color force is called quantum chromodynamics (QCD). The carriers of the color force are eight massless particles, colored gluons that, just as the quarks, cannot be observed in isolation. The quarks respond to the gluons because they carry color; in fact, quarks come in three colors. The electroweak theory together with QCD form the Standard Model of particle physics.

Since we aim to show how the familiar particles and interactions may arise in string theory, we now summarize the particle content of the Standard Model. We have already said that gravity appears automatically in string theory as a fluctuation of closed strings. Therefore, we will not focus on gravity, but rather on the other force carriers and the matter particles, both of which arise from vibrations of open strings.

The Standard Model includes twelve force carriers: eight massless gluons, the W^+, W^-, Z^0, and the photon. All of them are bosons. There are also many matter particles, all of which are fermions. The matter particles are of two types: leptons and quarks. The leptons include the electron e^-, the muon m^-, the tau t^-, and the associated neutrinos n_e, n_m, and n_t. We can list them as

$$\text{Leptons}: (n_e, e^-),\ (n_m, m^-),\ \text{and}\ (n_t, t^-). \tag{4}$$

Since we must include their antiparticles, this adds up to a total of twelve leptons. The quarks carry color charge electric charge and respond to the weak force, as well. There are six different types or "flavors" of quarks: up (*u*), down (*d*), charm (*c*), strange (*s*), top (*t*), and bottom (*b*). We can list them as

$$\text{Quarks}: (u, d),\ (c, s),\ \text{and}\ (t, b). \tag{5}$$

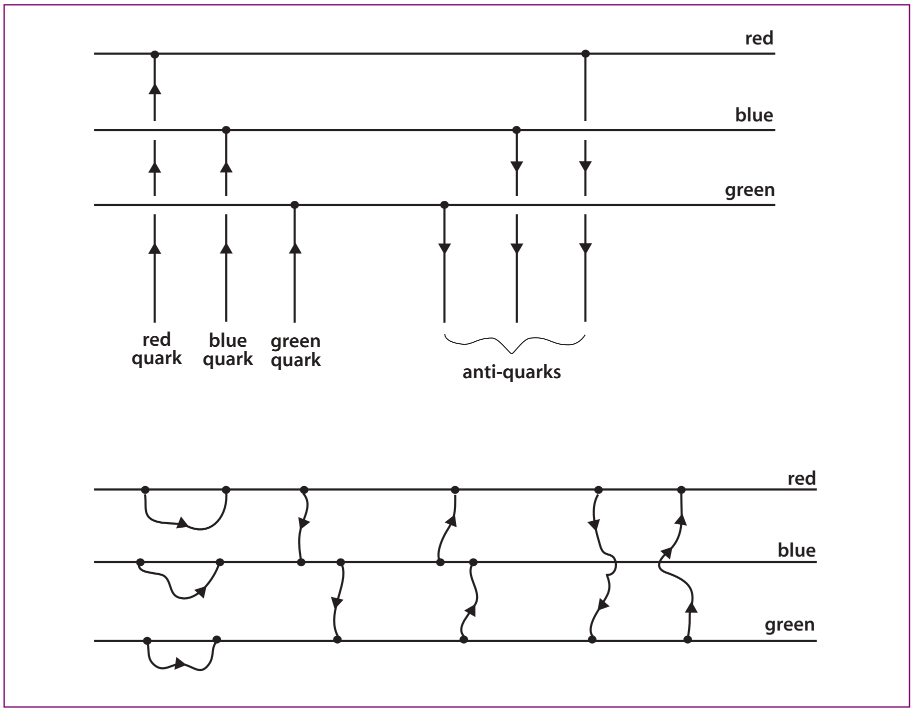
The *u* and *d* quarks, for example, carry different electric charges and respond differently to the weak force. Each of the six quark flavors listed above comes in three colors, so this gives 633=18 particles. Including the antiparticles, we get a total of 36 quarks. Adding leptons and quarks together we have a grand total of 48 matter particles.

Although the matter particles displayed above and some of the gauge bosons have masses, these masses are in some sense remarkably small. Consider the fundamental constants of nature: Newton's gravitational constant, the speed of light and Planck's constant. Since there are three basic units—those of mass, length and time—there is a unique way to construct a quantity with the units of mass using only the three fundamental constants. The resulting mass is called the Planck mass and its numerical value is about 2.2310^{-5} grams. While ordinary by the standards of macroscopic objects, this prototype mass is extraordinarily large when compared with the masses of elementary particles: it is twenty-two orders of magnitude larger than the mass of the electron, for example. It is in this sense that elementary particles are essentially massless.

The *chirality* of the electroweak interactions guarantees that the matter particles cannot acquire masses until electroweak symmetry breaking takes place. If one adjusts the scale of electroweak symmetry breaking to be small, the matter particles will be light. To understand the meaning of chirality, we recall that particles with spin are described in terms of left-handed and right-handed states. If the spin angular momentum points along the direction of the motion, the particle is said to be right-handed; if the spin angular momentum points opposite to the direction of motion, the particle is said to be left-handed. A left-handed electron, for example, is denoted as e_L^- and a right-handed electron is denoted as e_R^-. The

FIGURE 4

***Top:** Three parallel D-branes (shown as horizontal lines) are needed to produce the color interactions. The branes can be labeled by colors: red, blue and green. The left-handed quarks are open strings that end on the colored branes. A red quark, for example, is a string that ends on the red brane. The left-handed antiquarks are open strings that begin on the colored branes. **Bottom:** The open strings that begin and end on the brane configuration are gauge bosons. This brane configuration supports nine gauge bosons, eight of which are the gluons of QCD.*



electroweak interactions are chiral because the left-handed states and the right-handed states of the Standard Model particles respond differently to the weak forces; there is a fundamental left-right asymmetry. If we focus on the electron and the neutrino, for example, we have:

$$\begin{pmatrix} \mathrm{n}_{eL} \\ \end{pmatrix}, \; e^-_R, \, \mathrm{n}_{eR}. \tag{6}$$

The left-handed states in the doublet feel the weak interactions, while the right-handed electron and the right-handed neutrino states do not. A similar situation holds for the quarks. The left-handed states of the u and d quarks feel the weak interactions while the right-handed states do not:

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \; u_R, d_R. \tag{7}$$

The existence of mass requires couplings between left- and right-handed states that are not allowed as long as chirality holds.

D-branes and the Standard Model

D-branes are extended objects in string theory. Whenever we have open strings we also have D-branes, since the endpoints of open strings must lie on them. D-branes come in various dimensionalities. A Dp-brane is a D-brane that has p spatial dimensions. A D2-brane, for example, may look like a sheet of paper, and a D1-brane may look like a string. In four-dimensional spacetime, a D3-brane may fill the full extent of the three spatial dimensions, in which case we have a space-filling brane. Since D-branes extend in various dimensions we can imagine observers that live on D-branes.

String endpoints carry electric charge so, in order to represent a charged particle, we arrange to have a string with one endpoint lying on the D-brane. The other string endpoint must lie on another, possibly separate D-brane, otherwise the string would represent two oppositely charged particles, for a net of zero charge. A positively charged particle is represented by a string that ends on the D-brane, while a negatively charged particle is represented by a string that begins on the D-brane. In fact, the photons that couple to these charges arise from open strings with *both* endpoints on the D-brane. As required, these states have zero charge.

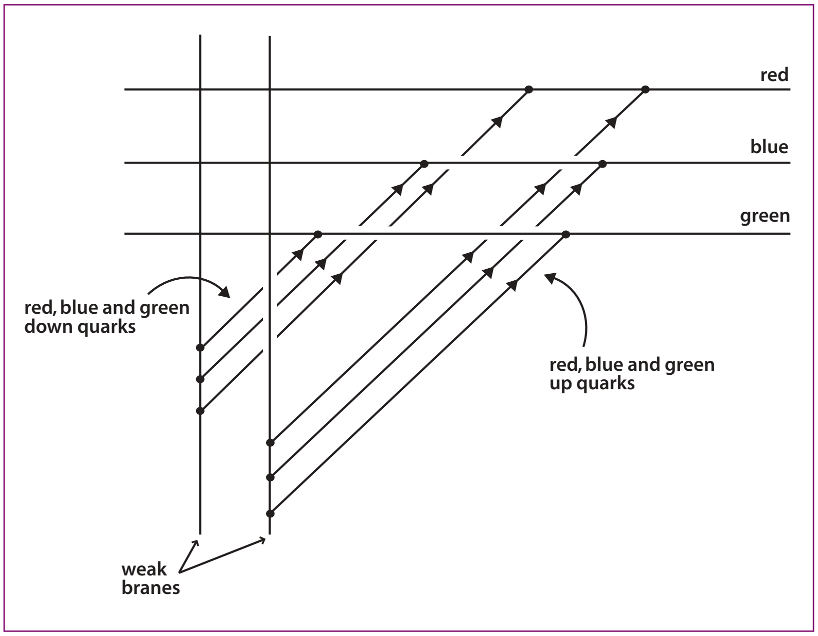
How can we get quarks using D-branes and strings? Since color is just a whimsical label for a kind of charge, to obtain three types of color we simply use three different D-branes: a red brane, a blue brane, and a green brane (*Figure 4*). To represent quarks we use strings that have one endpoint on a colored brane while the other endpoint lies on a different collection of branes, to be specified later. A string that ends on a green brane is a green quark, a string that ends on a blue brane is a blue quark, and a string that ends on a red brane is a red quark. Strings that *begin* on the colored branes are antiquarks. On the other hand, the gluons—the carriers of the color force—arise from strings that begin *and* end on the colored branes. With three D-branes, there are a total of nine such strings. Out of these, eight of them are the gluons we are looking for.

For any quark, one endpoint of the corresponding string lies on a color brane. Where does the other endpoint lie? The answer becomes clear once we consider the weak interactions. In order to produce the four gauge bosons of the electroweak interactions we need two new D-branes, two "weak branes." To draw the brane configuration, it is convenient to use a plane and represent the D-branes as lines. We take the weak branes to intersect the color branes, as shown in *Figure 5*. Let's now consider the two flavors of quarks indicated in (7). Since the left-handed *u* and *d* quarks feel the weak interactions (in addition to the color force) the strings that represent them must have their other endpoint on a weak brane. Given that we have two weak branes, we have a perfect fit: the left-handed *u* quarks are strings stretched from one of the weak branes to the color branes, while the left-handed *d* quarks are strings stretched from the other weak brane to the color branes.

The strings that represent the left-handed quarks stretch from one kind of brane to the other. The string tension forces the strings to have the minimum possible length, which in this case is zero, so they represent massless states that live at the points

Figure 5

The color branes intersect the two weak branes (shown vertically). Open strings localized near the intersection that stretch from the weak branes to the color branes are left-handed quarks. The two flavors of quarks (u and d) arise because there are two weak branes.



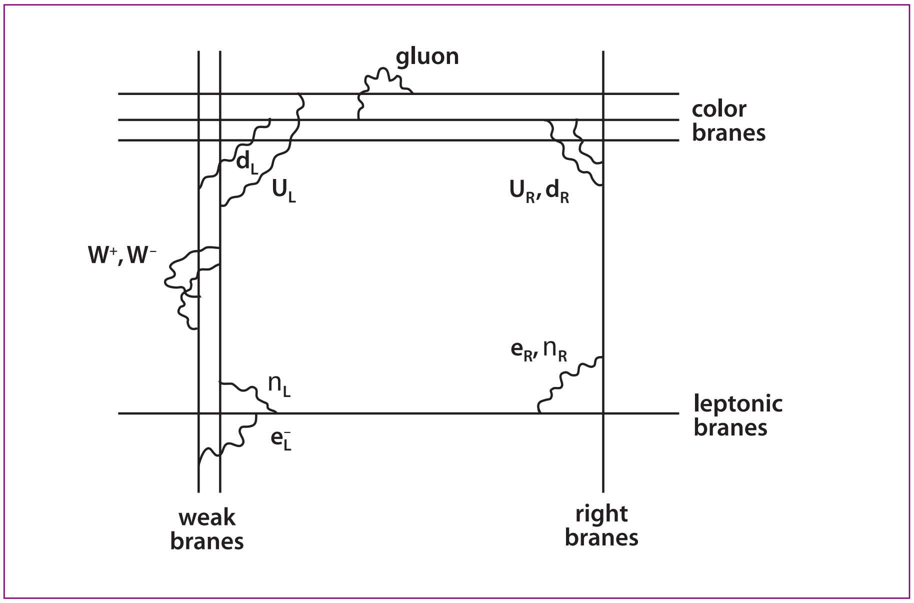


FIGURE 6

The full D-brane configuration in which open strings represent the familiar particles of the Standard Model. The vertical branes to the right are called "right branes" because they support the right-handed quarks (which do not feel the weak interactions). The horizontal branes at the bottom are called "leptonic branes" since they support the left-handed leptons (to the left) and the right-handed leptons (to the right).

where the branes intersect. Chirality is a property that guarantees that mass cannot be readily acquired. When D-branes intersect, there is no small displacement of the branes that eliminates the intersection, so the strings that stretch from one brane to the other cannot acquire mass. Chirality is a property of states that arise at brane intersections.

How do we get the right-handed quarks listed in (7)? Since these states feel the color force, the strings have one end on the color branes. Since they do not feel the weak interactions, they cannot have their other endpoint on the weak branes and consequently we need new branes. These new "right branes" must intersect the color branes for the states to be massless. As shown in *Figure 6*, the right-handed quarks stretch from the right branes to the color branes.

Let's now consider the lepton doublet that includes the left-handed neutrino and electron [see (6)]. These particles feel the weak interactions, so they are represented by strings that have one endpoint on the weak branes. Since they do not feel the strong interactions, the other endpoint in those strings must end on new "leptonic branes." The left-handed leptons are shown as strings localized at the intersection of the weak branes and the leptonic branes. Finally, let's consider the right-handed electron e^-_R and the right-handed neutrino n_{eR}. These particles feel neither the color force nor the weak force. They are represented by strings that stretch from right branes to leptonic branes, as shown at the bottom right corner of *Figure 6*.

We have exhibited the states that comprise one family of the Standard Model. The Standard Model has two additional families, with states completely analogous to those described in (6) and (7). These are obtained with additional intersections. The first models to give the precise spectrum of the Standard Model were constructed in 2001 by Ibanez, Cremades and Marchesano [3].

We have so far imagined the D-branes as D1-branes that are stretched on a two-dimensional plane. Let us finally show how the brane configuration fits into a ten-dimensional superstring theory. A physical setup requires an effective four-dimensional spacetime, so six of the spatial dimensions must curl up into a compact space of small volume. To visualize the brane configuration we assume that two out of the six extra dimensions are curled up into a two-dimensional torus (*Figure 7*). The D-branes are all chosen to be D4-branes, and three out of their four spatial directions fill our space. The last direction is chosen to appear as a line on the two-dimensional compact torus. So, in fact, *Figure 6* was a picture of the D-branes as seen on the torus, a close-up that does not quite show how the D-branes are fully wrapped around the torus. The strings that represent the Standard Model particles are localized at the brane intersections and are perceived as particles.

While there are string constructions that give precisely the matter content of the Standard Model, no one claims to have a derivation of particle physics from strings. For this, one must also show that symmetry breaking works out correctly and particles acquire their familiar masses. This has not yet been done. I hope, however, to have demonstrated that familiar features of our observed universe can emerge from string theory.

Outlook

We may wonder what are the possible outcomes of an exhaustive search for a realistic string model. One possible outcome (the worst one) is that no string model reproduces the Standard Model. This would rule out string theory. Another possible outcome (the best one) is that one string model reproduces the Standard Model. Moreover, the model represents a well-isolated point in the space of all string solutions. The parameters of the Standard Model are thus predicted. The number of string models may be so large that a strange possibility emerges: there may exist many string models with almost identical properties, all of which are consistent with the Standard Model to the accuracy that it is presently known. In this possibility there may be a significant loss of predictive power. Other outcomes may be possible.

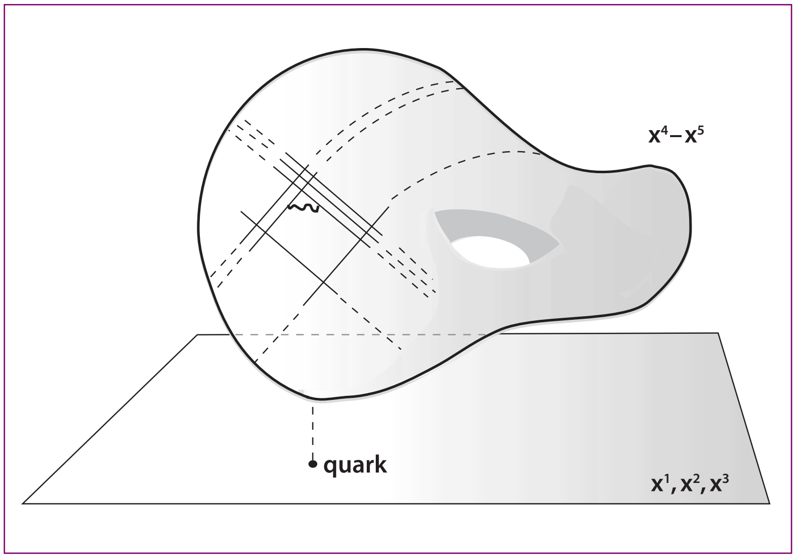


Figure 7

The intersecting D-brane configuration. To visualize a compactification we must imagine that a compact torus, such as the one shown in the figure, exists on top of each point of ordinary three space (represented as a plane with coordinates X^1, X^2, and X^3). The D4-branes fill three-space and have one direction along the torus. The D-branes appear as lines on the torus. A left-handed quark is an open string that stretches from weak to color branes on the torus. It is perceived as a particle in three-space.

New experimental input will also help us determine if string theory describes our universe. The recent discovery of a nonzero positive cosmological constant has suggested new directions of investigation based on cosmological properties of strings. A discovery of supersymmetry would be a strong indication that string theory is correct because supersymmetry is generic in string theory—it is almost a prediction. The discovery of extra dimensions, perhaps surprisingly large ones, would also have dramatic implications. Most likely, finding out if string theory describes our universe will require a greater mastery of the theory. String theory is in fact an unfinished theory. Much has been learned, but there is no complete formulation of the theory and its conceptual foundation remains largely mysterious. String theory is an exciting research area because the central ideas remain to be found.

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