Is the Whole Universe Composed of Superstrings?*

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The Michelson–Morley experiment, as interpreted by Einstein, played a crucial role in the revolution in physical theory of the first part of the twentieth century, in which special and then general relativity as well as quantum mechanics changed radically the way we think about the universe. It is appropriate to a centennial celebration of that experiment to discuss the possibility that a theory of elementary particles may finally have been discovered that successfully harmonizes quantum mechanics and general relativity.

Elementary particle physics is the study of the fundamental building blocks of which the whole universe, including us, is made. Each kind of particle has the same properties wherever found anywhere in the universe. The laws of those particles and of their interactions constitute the fundamental microscopic laws of natural science. The macroscopic laws concern the boundary condition at the early moments of the expansion of the universe, especially the fact that some 15 or 20 billion years ago it was a tiny, dense, hot, expanding ball. The two subjects, elementary particle physics and early cosmology, have practically merged, and nowadays many of the important ideas in cosmology are coming from elementary particle physics. Together, the two subjects constitute the fundamental laws of natural science, in the small and in the large. They underlie all of physics and chemistry, and in turn they form the substrate for the rest of natural science.

This article discusses theory. There isn't room for more than a glance at experiment and observations, but we must remember that theoretical science and experimental or observational science have to advance as partners. Sometimes theory is ahead and predictions are confirmed by observation. At other times experimentalists find something unexpected and theorists have to go back to the drawing board and start over again.

Our subject, superstring theory, to which we will get after a long introduction, has so far very little basis of comparison with experiment, although it is fantastically promising as a theory, as I shall try to make clear. We must remember that ultimately observation and experiment will be the arbiters of its validity.

I shall start by reviewing some aspects of elementary particle theory that are relatively secure, confirmed in large part by experiment. When we get to more speculative material, I shall issue an appropriate warning, which is necessary because both kinds of theoretical ideas sound equally crazy.

All of modern theoretical physics is based on a few principles. The most important of them is that mysterious discipline called quantum mechanics, which was invented some sixty years ago. It is not a specific theory, but rather the framework within which all correct theories have to fit. Nobody feels perfectly comfortable with it, because it is what the social scientists call counter-intuitive, but we know how to use it, and it works perfectly.

Einstein's principle of relativity also seems to be perfectly correct, and so does causality, the very simple principle that a cause comes before its effect. If we put these three principles together we get the fundamental framework of quantum field theory, within which any respectable work or even speculation in our field has to be carried out.

In quantum field theory, every force is carried by a particle that is the quantum of that force. For electromagnetism, the quantum is the famous photon, very well confirmed by experiments since it was suggested in 1900. We have a beautiful theory, quantum electrodynamics, which describes electrons and their interactions with photons. It is now about 58 years old and it is a perfect model of a successful theory, confirmed up to an accuracy of many decimal places by observation, so that it deserves its nickname of QED. In any quantum field theory we can draw funny little pictures, invented by one of my colleagues, which are supposed to give the illusion of understanding what is going on in field theory. In Fig. 1 we have electrons exchanging photons to get the electromagnetic force between them. The electrons have negative electric charge, as indicated by the minus signs. (The sign convention is due to Benjamin Franklin and has no special importance.) If you know some physics, you will note that the emission of the photon by one electron and its absorption by the other seem to be forbidden by the laws of energy and momentum conservation; but if you know still more physics you will understand that in the Pickwickian sense of quantum mechanics, a photon can still be "virtually" exchanged because over short space-time intervals those laws do not have to be exactly obeyed. (That is, by the way, an example of the "Heisenberg uncertainty principle" in operation.)

The history of our field over centuries is that we have come to understand matter in smaller and smaller chunks. We have learned on several occasions that what we thought was fundamental is in fact made of smaller things: molecules and crystals are made of atoms or ions; the atoms or ions are made of nuclei with electrons around them, as is well known; and the nuclei are made of neutrons and protons, as physicists began to understand around 1932, when the neutron was discovered. Now we know that the neutrons and protons are in turn made of quarks, where "quark" is the obvious name for their fundamental constituent.

The prescription for making a neutron or proton out of quarks is that you take three quarks. The electrically neutral neutron (electric charge zero) is composed of one u quark with charge $+\frac{2}{3}$ and two d quarks of charge $-\frac{1}{3}$ each, giving a total charge of zero. For the proton, the charge of which is taken to be the fundamental unit of charge (so that its electric charge is $+1$), we have two u's and one d. Adding up $\frac{2}{3}$, $\frac{2}{3}$ and $-\frac{1}{3}$, we get 1.

The u and d are called flavors of the quark, and there are actually more flavors, although not as many as 31. Probably there are six. Besides flavor, the quarks also have a very important characteristic that we call by the nickname of color, although it has absolutely nothing to do with real color. The name is just a joke and a metaphor. There are three colors, and we call them red, green and blue, after the three fundamental colors in a simple theory of human color vision. The prescription for a neutron or proton is that you take one quark of each color, i.e., a red quark, a green quark, and a blue quark, in such a way that color averages out. Since in vision, white can be thought of as a mixture of red, green, and blue, we can use the metaphor to say that the observed particles like neutron and proton are white. Color is averaged out in the observed particles and only inside them can colored objects exist.

Just as electrons have the electromagnetic force between them that comes from the virtual exchange of quanta called photons, with which many people are familiar, so the quarks are bound together by the exchange of other quanta called gluons, with which most people are unfamiliar. These quanta "glue" the quarks together to make the neutrons and protons and other observable nuclear particles. The gluons pay no attention to flavor – we can say that they are "flavor-blind." However, they are very sensitive to color, and for different situations there are actually different kinds of colored gluons. In Fig. 2 we see how a red quark turns into a blue one with the virtual emission of a red-blue gluon, which is then virtually absorbed by a blue quark, turning it into a red one. In another situation we have the exchange of a blue-green gluon. We can say that gluons are colorful, and we shall see how that makes an enormous difference to the character of the theory that applies to quarks and gluons.

Around 1972 some of us proposed a definite quantum field theory for quarks and gluons to describe the nuclear particles and to explain the old mystery of the nuclear force. The theory is called quantum color dynamics, or quantum chromodynamics if you like to use the Greek word for color. It seems to be correct, although not yet absolutely proved. The nuclear particles are all made of quarks and gluons behaving according to this detailed mathematical theory. We can put together a sort of dictionary as illustrated in Fig. 3. In quantum electrodynamics (QED), we had electrons interacting through the exchange of photons; in quantum color dynamics (QCD), we have the colored quarks of various flavors interacting through the colorful gluons. The newer theory seems to be just as valid as the older one.

There is an important difference between the two theories. Whereas in QED, the quanta that carry the electromagnetic force are electrically neutral, the situation in QCD is different: the quanta that carry the color force are themselves colorful. As a result, the equations have a couple of extra terms, the solutions of the equations are different, and it turns out that the color force is completely different in its properties from all other known forces: it does not drop off at large distances like gravity or electromagnetism. It stays big, even up to infinite distance. That in turn has the effect that all colored and colorful particles like quarks and gluons are permanently trapped inside the white observable objects like neutron and proton. The constituents cannot emerge to be detected individually, although there are numerous experiments that reveal these contituents inside.

We believe (although the relevant calculations have not been worked out completely by any means) that the nuclear force, which holds the neutrons and protons together in the nucleus, can be understood in terms of the basic quark- gluon interaction. We seem to have solved, at least in principle, one of the main problems that faced elementary particle physics when I was a graduate student.

Now there is more to the world than the atomic nucleus. In an atom we have electrons surrounding the nucleus. The electron has an electric charge of -1, but it has no color and does not feel the nuclear force. (An electron inside the nucleus, such as one of the innermost electrons of very heavy atoms, feels only the electrical force of the protons.) However the electron does in a sense have flavor. It has a kind of silent partner called the electron neutrino, which represents, so to speak, another flavor of the electron, just the way u and d are different flavors of quark. The electron neutrino, which was first suggested theoretically by Wolfgang Pauli in 1930, feels neither the nuclear force nor the electromagnetic force, and it can pass right through the earth with very little probability of interacting. The solar neutrinos, produced in the nuclear reactions in the center of the sun, come down from the sun during the day, and they come up through the earth at night.

The poet and novelist John Updike, when he read about this situation around 1960, was inspired to write the poem, "Cosmic Gall."
[See poem attached.]
(In the third line it is tempting to employ scientific license and alter "do not" to "scarcely.") Unfortunately detection of solar neutrinos is still fraught with many

problems. The rate of detection is much lower than predicted, leading my colleague Willy Fowler to suggest that maybe the sun went out some time ago and the news has not yet reached the surface. I think not many people believe that explanation, but if it is true, it means we are heading for a real energy crisis.

The electron neutrino can be detected because there is a force in which it participates, along with the electron: the so-called "weak force," which allows, for example the reaction

$$\nu_e^0 + n \rightarrow e^- + p^+$$

or, more basically, in terms of quarks,

$$\nu_e^0 + d^{-1/3} \rightarrow e^- + u^{+2/3}.$$

The electron neutrino turns into an electron, while the d quark turns into a u quark of the same color. As indicated in Fig. 4, this process occurs through the virtual exchange of a heavy, electrically charged quantum called $X^{\pm}$, which theorists (including me) predicted in 1957, and which was finally discovered experimentally in 1983. The discovery of the quantum, which is often called $W^{\pm}$ these days (though I adhere to my original name for it), procured a Nobel Prize for Carlo Rubbia and Simon van der Meer.

The electromagnetic and weak forces can be thought of as "flavor forces," since the electric charge varies with flavor and the weak force involves the changing of flavor. During the 1950's and 1960's, a sort of quantum flavor dynamics was formulated, including quantum electrodynamics and a theory of the weak force. Among the successful predictions of quantum flavor dynamics was that of a new flavor force that permits simple scattering processes for neutrinos, like:

$$\nu_e^0 + p \rightarrow \nu_e^0 + p$$

and

$$\nu_e^0 + n \rightarrow \nu_e^0 + n$$

or, more basically, in terms of quarks:

$$\nu_e^0 + u^{+2/3} \to \nu_e^0 + u^{+2/3}$$

and

$$\nu_e^0 + d^{-1/3} \to \nu_e^0 + d^{-1/3}$$

Here what is involved is the virtual exchange of a heavy, electrically neutral quantum called Z^0, as shown in Fig 5. That quantum, too, was discovered by Rubbia, van der Meer, et al.

Quantum flavor dynamics, with its four quanta (photon, $X^{\pm}$, Z^0), has recently scored considerable success in predicting the results of experiments, but, from the theoretical point of view, certain aspects of the theory make it seem provisional and likely to be embedded in a bigger and better theory.

Let us summarize, in Fig. 6, what we have described so far: the two flavors e^- and ν_e^0; the two flavors of tri-colored quark, $d^{-1/3}$ and $u^{+2/3}$; the flavor forces, including electromagnetism, acting on the flavor variable, carried by the photon and by the quanta $X^{\pm}$ and Z^0, and described by quantum flavor dynamics; and the color forces, acting on the color variable (not present for e^- and ν_e^0), carried by the colorful gluons, and described by quantum color dynamics.

Amazingly, Nature does not find this list of elementary particles to be sufficiently long. There are at least two ways in which we must extend it.

First, let us describe the electron and the neutrino, treated as two flavors, and the tri-colored d and u quarks, with their two flavors, as a sort of family of particles. At higher masses, there are two more such families. (See Fig. 7.) The so-called muon μ^-, a sort of heavy electron discovered at Caltech by Carl Anderson and Seth Neddermeyer in 1937, turns out to have its own neutrino ν_μ^0, and there are two more flavors of quark to go with them, called the strange quark $s^{-1/3}$ and the charmed quark $c^{+2/3}$. (Note the frequently seen bumper sticker: PHYSICISTS DO IT WITH

CHARM.) The tauon τ^-, a still heavier electron, discovered at SLAC (the Stanford Linear Accelerator Center) around 1974 by Martin Perl et al., appears to have its own neutrino as well, ν_τ^0, and seems to be accompanied by two more flavors of quark, $b^{-1/3}$ and $t^{+2/3}$. Actually the existence of $t^{+2/3}$ has not yet been demonstrated experimentally, but it is certainly expected by theorists, who ought to commit seppuku if it is not found. (My colleague "Murph" Goldberger, now President of Caltech, used to describe this process as "falling on your fountain pen." These days, fountain pens are scarce. Besides, we know that the ancient Roman hero who wanted to kill himself after a defeat had a trusty retainer to hold his sword – could a graduate student hold the fountain pen steady enough?)

If we succeed in understanding the existence of the family made up of e^-, ν_e^0, u, and d, we must also explain the tripling of the family – who ordered all those extra flavors?

Another way in which the list of elementary particles must be extended is by adding anti-particles. In quantum field theory, for every particle, there is an anti-particle with the same mass and with equal and opposite values of electric charge and of certain other quantities. For some electrically neutral quanta, such as the photon and Z^0, the anti-particle is the same as the particle. For the other quanta we have listed, the anti-particles are already on the list; for example X^+ and X^- are anti-particles of each other, and so are, for example, red-blue and blue-red gluons. Thus, for the quanta, including anti-particles introduces nothing new. However, for the three families we have discussed, that is not the case – the anti-particles are all distinct from the particles, as indicated below using the first family as an example:

$$e^- \leftrightarrow e^+,$$

$$\nu_e^0 \leftrightarrow \bar{\nu}_e^0,$$

$$u^{+2/3} \leftrightarrow \bar{u}^{-2/3},$$

$$d^{-1/3} \leftrightarrow \bar{d}^{+1/3}.$$

We have now described $2 \times 3 \times 8 = 48$ members of the three families, including the anti-particles, plus 4 electro-weak quanta and 8 gluons, making 60 different particles so far. The layman will naturally ask, "Why should there be so many different kinds of elementary particles?" The elementary particle specialist asks exactly the same question.

One possible answer is that quarks, electrons, and so forth, and perhaps the quanta as well, are composite in their turn. Although it is true that they have not shown any sign of compositeness so far, the evidence for it could still turn up at very high energies. However, there is no convincing composite scheme that reduces drastically the number of fundamental objects needed.

Chairman Mao expressed an opinion on this subject, with which I suppose it was advisable to agree if you lived in China before the suppression of the "gang of four." He said there would be an infinite regression, with nucleons composed of quarks, quarks of sub-quarks, sub-quarks of sub-sub-quarks, and so on. No appealing theory of this type has turned up, and even in China, under the milder rule of the present leadership, I don't think the "infinite series of layers" scheme is being actively pursued.

There is another approach, which need not involve seeking objects more fundamental than today's elementary particles. Instead, it uses the assumption that Nature has chosen a special elegant mathematical scheme that involves a particular list of elementary particles, presumably the ones we know plus others. (Actually, it is not excluded here that the really elementary particles might be constituents of the ones with which we deal today, but that complication is probably unnecessary and I shall not discuss it further.)

The elegant mathematical scheme would involve a master equation for a single field with many components corresponding to the various elementary particles. In this approach, simplicity lies not in economy of particles but in economy of principles.

The search for such a single beautiful master equation evidently involves the attempt to unify the various forces. Unlike the material I have presented so far, what we are now discussing is highly speculative, not supported by a rich body of experimental evidence. It is natural to inquire how such speculation is carried out. The accompanying cartoon, plagiarized from the New Yorker, shows the master at work, trying out various theories and discarding them until he finds the right one! (Fig. 8)

In fact, the most important tool of the theoretician's trade is not the fountain pen, or the ball-point pen and mechanical pencil that have succeeded it, but the waste basket. We write out the equations of promising theories on sheets of paper and then crumple up the sheets and throw them away when the theories turn out to be either self-inconsistent or else incompatible with some well-organized body of theory supported by unshakeable experimental evidence. Rarely, a proposed theory survives this process and goes on to be studied seriously and eventually tested experimentally.

During the 1970's, most speculation about the unification of the forces of Nature involved schemes that embraced quantum flavor dynamics and quantum color dynamics, together with new forces mediated by new quanta, in what we might call a "quantum unified dynamics." This task was not quite so daunting as it might appear, because both flavor and color dynamics belong to the same class of theories, called Yang-Mills theories after the two theorists who proposed them in the 1950's. What was being sought was a unified Yang-Mills theory, referred to by some theorists as a "grand unified theory" or GUT. (The name GUT is inappropriate, in my opinion, for two reasons: First, there was no previous unification, since quantum flavor dynamics exhibits only a mixing, not a true unification, of the electromagnetic and weak forces; and second, one should not speak of "grand unification"" when gravitation is being ignored.)

Several related unified Yang-Mills theories look promising, but they are difficult to test because the effective unification takes place at an energy at least 10^{13} (ten trillion) times higher than that accessible at today's largest accelerators. The theories thus represent a bold extrapolation from what is known, and we cannot hope to explore directly the energy range involved.

Fortunately, there are some predictions of unified Yang-Mills theory that can be tested at low energies, even though they depend on the properties of the theory at the enormously high energy of effective unification. The most important prediction of a typical unified Yang-Mills theory is that of proton decay.

Since the proton was known to decay, if at all, at a rate slower than 10^{-30} per year (!), most theorists had assumed that it was perfectly stable, although we had never found a good reason for its stability. In the early 1970's, with the advent of speculation about unified Yang-Mills theories, which predict rates of decay something like 10^{-32} per year, the rush to find proton decay in the laboratory was on. The search must be carried out far underground, where false signals from cosmic rays are not a problem. Experiments are under way in a salt mine in Ohio, a silver mine in Utah, and a tunnel under the Alps, but so far no convincing cases of proton decay have turned up, even though the upper limit on the rate has been brought down near 10^{-32}.

Still, most theorists are betting on proton decay, perhaps at a somewhat lower rate, because of a point made long ago, even before unified Yang-Mills theories were proposed, by Andrei Sakharov, the Soviet physicist, weapons designer, and activist for peace and human rights. He pointed out that proton instability could help to explain the apparent preponderance of matter over anti-matter in the universe.

Meanwhile, a number of theorists have gone beyond thinking about unified Yang-Mills theories to working on the ultimate problem of elementary particle theory, the attempt to unify quantum flavor dynamics and quantum color dynamics (perhaps brought together in a unified Yang-Mills theory) with a quantum version of Einstein's "general relativity" theory of gravitation. Here we come, finally, to the attempt to achieve a complete synthesis, to find a single theory that would describe all the forces and all the elementary particles of Nature.

It was Einstein himself who made unified field theory a famous goal and tried hard to reach it. Even though he was the greatest theoretical physicist since Newton, he failed to find what he was seeking. He worked only with gravitation and electromagnetism, since in his time the weak and nuclear forces were poorly understood; although the electron was well known, he did not use it in his work, hoping that it would emerge as a prediction; he knew nothing, of course, of quarks and gluons and other recently discovered elementary particles; and, most important, he ignored quantum mechanics, which he found philosophically objectionable. It is hardly surprising that Einstein did not succeed in this endeavor that occupied the last two decades or so of his life.

Today, the prospects look much brighter, and, in fact, in superstring theory, we have a promising candidate for a true unified theory.

Any correct theory must include Einstein's general-relativistic theory of gravitation as an approximation, and we know that when quantum mechanics is brought in as well, the gravitational force must be carried by a quantum, which we call the graviton, and many properties of the graviton can be readily deduced from Einstein's theory. (For example, it is electrically neutral, it travels with the speed of light like the photon, and it has two units of a certain quantity called "spin.")

The graviton is extraordinarily difficult to detect, because the gravitational force is very feeble between elementary particles, although most of us don't think of gravity as feeble while we are in the pull of a whole planet. (Even classical gravitational waves have not been directly detected so far, although there are experimental physicists working hard on that project.) However, the theoretical arguments for the graviton are overwhelming.

What a completely unified quantum field theory must do is to generalize a quantum version of Einsteinian gravitation, based on the graviton, to make it consistent, and to have it include all the other forces and particles.

We are now at the point in this article where we can begin to describe superstring theory, which has given us the only serious candidate for such a unified theory.

Superstring theory obeys a fascinating principle of self-consistency that is called the "bootstrap" principle because it allows the whole system of elementary particles, in a metaphorical sense, to "pull itself up by its own bootstraps." This principle imposes a very stringent condition on the theory. It was first proposed twenty-five years ago by Geoffrey Chew and Steven Frautschi in connection with theories of the nuclear particles alone.

I remember objecting, in the middle sixties, to one aspect of the bootstrap research of Chew and his collaborators, namely that they utilized only a very small number of particle types in their theoretical models. I suggested that it would be much better to try to include an infinite set of particles. Three Caltech postdoctoral fellows (Richard Dolen, David Horn, and Christoph Schmid) wrote a seminal paper on "duality" embodying this idea. Shortly afterwards the theorist Gabriele Veneziano produced an ingenious model of an infinite set of particles satisfying the "duality" version of the bootstrap conditions.

Unfortunately the Veneziano model had some apparently unacceptable features, but in 1971 John Schwarz and André Neveu, working at Princeton University and making use of some work of Pierre Ramond, developed the first version of superstring theory, which was to overcome the difficulties of the Veneziano model.

Thus work on superstring theory began fifteen years ago as an attempt to describe only the nuclear particles (neutron, proton, mesons, etc.), which are now known to be composed of quarks, anti-quarks, and gluons. Even then many of us believed in a theory based on these constituents, but quantum color dynamics had not been fully developed, and there was a good deal of discussion of alternative theories.

At that time, the energy scale of superstring theory was thought to be around 1 GeV, near the rest energy of the neutron or proton.

As a theory of the nuclear particles, superstring theory was not notably successful. In particular, a certain theoretical particle kept cropping up, with special properties, which had no counterpart among the real nuclear particles. All efforts to suppress this unwanted particle in the theory were unsuccessful.

Soon afterwards, around 1972, the present formulation of quantum color dynamics was achieved, and fairly soon it was acknowledged to be, most probably, the correct theory of the nuclear particles. Most theorists therefore stopped working on superstrings. But John Schwarz continued to pursue research on the subject. In 1972, we invited him to Caltech.

Two years later, we had a brilliant young visitor from France, Joël Scherk, who collaborated with Schwarz on a radical reinterpretation of superstring theory. They looked again at the unwanted particle in the theory – electrically neutral, traveling with the velocity of light, possessing two units of "spin" – and decided it was not a nuclear particle at all – it was the graviton!

Studying superstring theory more closely, they found it contained a quantum version of Einsteinian gravitation as an approximation, along with many other particles and forces. They reached the startling conclusion that they were dealing with a possible unified field theory of all the elementary particles and all the forces of Nature.

In order to effect the change from a (wrong) theory of the nuclear particles alone to a (possible) theory of all the particles and all the forces, Scherk and Schwarz had to alter the mass scale of the theory by an impressive factor, changing it from around 1 GeV to around 10^{19} GeV, the fundamental energy scale of quantum gravitation. This "Planck energy" (around the rest energy of a postage stamp) is constructed from the fundamental constants of Nature: the velocity of light, c, the constant of quantum mechanics $\hbar$, and Newton's constant of gravitation, G or κ^2. Corresponding to the "Planck energy" is the fundamental "Planck length" of about 10^{-33} cm. Just as the energy scale is about 10^{19} times higher than the rest energy of a neutron or proton, so the length scale is about 10^{19} times smaller than the size of a neutron or proton. In superstring theory, because it generalizes quantum gravitation, we are making an even bolder extrapolation from attainable energies and distances than in unified Yang-Mills theory.

The word "string" appears in the name of the theory because the particles are described, on the length scale of about 10^{-33} cm, not as mathematical points (as in usual quantum field theory) but as tiny "strings," typically loops. (It was Yoichiro Nambu of the University of Chicago and his collaborators who first emphasized the string interpretation of the theory around the beginning of the 1970's.)

Analyzing such a string into modes, like a violin or piano string with its harmonics, we get the equivalent of an infinite number of kinds of point particle. Thus, in superstring theory, the number of elementary particles is infinite.

The infinite set of particles is described, however, by a single "string field" obeying a single fundamental equation.

We begin to understand why we find a large number of different kinds of elementary particles. But why don't we find an infinite number? In the theory, only a finite number of the particles have masses that are very small compared to the huge "Planck mass." These low-mass particles are the only ones we have a chance of detecting.

The known particles, as we have seen, number about sixty (or sixty-one, including the graviton). Allowing for undiscovered ones, we may guess that the low-mass particles may number in the hundreds. Why should that be so? We shall have a hint of that. But why are the masses of the known ones so tiny (10^{-17} to 10^{-22}) compared to the Planck mass? That we do not know. Somehow such tiny numbers must be generated within the theory if it is to be correct, because superstring theory has "no free parameters," nothing to adjust to get agreement with observation.

The name "superstring" contains the prefix "super" because the theory possess a broken symmetry called "supersymmetry" between the two great classes of elementary particles, "fermions" and "bosons."

"Fermions," named after Enrico Fermi, include the three families of particles that contain the electron, the quarks, and so forth. They obey the "exclusion principle," which means they cannot stand to be in the same quantum state at the same time.

"Bosons," named after the Indian (Bengali) physicist S.N. Bose, include the quanta such as photon, gluons, and graviton. They love to be in the same state at the same time.

The fact that photons are bosons (pointed out almost seventy years ago by Bose and by Einstein) supplies the basic principle of the laser beam, in which all the photons have, to a high accuracy, the same energy and the same direction.

The broken "sypersymmetry" between fermions and bosons means that at sufficiently high energies (and we hope that these high energies will be low enough to be attainable in experiments at accelerators) we must find partners as follows:

for the photon (a boson), a heavy "photino" (a fermion);

for the gluons (bosons), heavy "gluinos" (fermions);

for the electron (a fermion), a heavy "selectron" (boson);

for the quarks (fermions), heavy "squarks" (bosons); etc.

Please do not blame me for names like "squark."

These "superpartners" of known particles are being sought at existing accelerators (Fermilab near Chicago and the SPS at CERN, the European Council for Nuclear Research, near Geneva, Switzerland) and will be sought at higher energy accelerators (LEP, being built by CERN in France near Geneva, and the SSC or superconducting super-collider, which we hope the U.S.A. will build).

A remarkable property of superstring theory is that its self-consistency seems to fix the number of spatial dimensions, and that number is not three. Instead, the theory appears to work only in nine spatial dimensions, giving a ten-dimensional space-time. Joan Cartier, a theoretical physicist who is also a cartoonist, has shown, in the accompanying drawing, how a lecture on this subject appears to her. (Fig. 9.)

What has become of the other six dimensions? If they are taken literally, it must be supposed that, unlike the familiar dimensions, they have not outgrown the size they had when the universe was in the first tiny fraction of a second of its expansion. Instead, at every point in three-dimensional space, the extra dimensions are curled up into a minute structure that has roughly the size of the Planck length, around 10^{-33}cm. This is so small that the extra dimensions do not play much of a role as such; but it turns out that the nature of the six-dimensional structure is crucial in determining the broken symmetries of the system of elementary particles. Much important research on that subject has been carried out by Edward Witten and his collaborators at Princeton University.

To get some idea of how to think of extra spatial dimensions, imagine that we are all "flat-landers" with only two dimensions, living in a two-dimensional world, and that some flat savant announces to us that he has good news and bad news: the good news is that we all have a new dimension, height, that we never knew about before; the bad news is that no flat-lander and no place in flat-land has a height greater than around 10^{-33} cm.

Since 1986, the notion has gained ground that in the solution to the superstring equations the extra dimensions do not have to be taken literally; they can be treated as mathematical constructs instead. The behavior of the extra dimensions remains, however, intimately connected with the symmetry pattern of the elementary particles and their interactions.

During the period from 1974 to 1983, there was considerable activity in the world of theoretical physics on supersymmetry and related questions, but very little on superstrings outside Caltech. We were continuing to maintain a nature reserve for an endangered species, the superstring theorist, with help from the Department of Energy and from the Fleischmann Foundation. That Foundation gave us generous support just as it was liquidating itself, a convenient arrangement since we had only to account for the legitimacy of our expenditures and not for the relevance of our speculations.

Starting around 1980, a frequent visitor was Michael Green, from London. He and Schwarz have been collaborating for the last seven years or so, and in 1983 and 1984 they produced some exciting results (some of them achieved during summer work in the stimulating atmosphere of the Aspen Center for Physics, Aspen, Colorado.)

To appreciate the first one, it is necessary to understand that quantum field theory is usually plagued by the occurrence of infinite quantities in calculations. Naïve calculations typically take the form

FINITE TERM + INFINITE CORRECTION + WORSE INFINITE CORRECTION + ...
Years ago, I had become so used to working with such formulae that someone asked me "Murray, what would you do if a calculation converged on you?"

Now in successful theories like quantum color dynamics or quantum flavor dynamics, the infinities can be absorbed into a few quantities, which can be arbitrarily set equal to finite, but uncalculable values. We obtain the finiteness at the price of the uncalculability. This process, which is called "renormalization," amounts to sweeping infinities under the rug, as Joan Cartier shows us in another of her cartoons. (Fig. 10.)

Now a straightforward quantum version of Einstein's general-relativistic theory of gravitation leads to infinities that are not even renormalizable. This has been known for many years for the case where the theory treats not only the graviton but other kinds of matter as well. It has recently been shown by Marc Goroff and Augusto Sagnotti that even for gravitons alone there are unrenormalizable infinities. In other words, no Band-aid will fix the quantum version of Einsteinian gravitation. A radical generalization is needed, such as superstring theory provides.

Schwarz and Green showed, in 1983 and 1984, that superstring theory seems to give only finite results. No infinities appear in the calculations, not even renormalizable ones. Moreover, superstring theory is the only known generalization of quantum gravitation is free of unrenormalizable infinities.

In 1984, Schwarz and Green made another discovery. Superstring theory was constructed using a system of elementary particle symmetries called a "Lie algebra" after the nineteenth century Norwegian mathematician Sophus Lie. These symmetries are present in addition to supersymmetry. It had been thought that there was an infinite variety of such algebras that could be used, for example, one with three independent symmetries, or one with six, or one with ten, and so forth. But Schwarz and Green showed that self-consistency restricted the choice to just two possibilities, called SO_{32} and $E_8 \times E_8$, each with 496 independent symmetries!

Now there is a relation, albeit a distant one, between the number of independent symmetries and the number of different kinds of elementary particle that have very low masses compared to the Planck mass. Thus for the first time we have a hint as to why the number of low-mass particles is something like a hundred, or hundreds.

The discovery that the choice of symmetry system was restricted to only two, both with 496 symmetries, created great excitement in the world of theoretical physics, especially coming just after superstring theory was known to be finite.

We may well ask, "How could a theory based on the number 496 be wrong?"

In any case, theoretical physicists around the world rushed to jump on the superstring bandwagon. In December 1984, a team of four theorists at Princeton University (David Gross, Jeffrey Harvey, Emil Martinec, and Ryan Rohm, known, of course as the "Princeton string quartet") found a new form of superstring theory, using the number 496, and based on the symmetry system $E_8 \times E_8$. Their version, which they call the "$E_8 \times E_8$ heterotic" superstring theory, looks like the best one for understanding the structure of the elementary particle system as revealed so far by experiment. Why Nature should have chosen this form of superstring theory rather than the two others that also utilize the number 496, we do not know. That is a puzzle that we shall have to solve.

Let us summarize what we have discovered about the virtues of superstring theory. It gives us:

an elegant, self-consistent quantum field theory

generalizing Einstein's general-relativistic theory of gravitation treated quantum-mechanically,

in the only known way that does not produce infinities,

parameter-free,

based on a single string field

but yielding an infinite number of elementary particles,

some hundreds of which would have low mass (although we don't know why they would be so very low!)

including particles with properties like those of electrons, quarks,photons, gluons, etc.,

with the underlying symmetry system essentially determined,

and with the symmetry breaking connected with the behavior of some extra, but perhaps formal dimensions.

There are certainly some indications that our colleagues may have found the "Holy Grail" of fundamental physics.

But only calculations and their comparison with experiment will allow us to tell. In our science, no amount of eloquence will save a wrong theory.