# A Unified Physics by 2050?

by Steven Weinberg

**Experiments at CERN and elsewhere should let us complete the Standard Model of particle physics, but a unified theory of all forces will probably require radically new ideas**

One of the primary goals of physics is to understand the wonderful variety of nature in a unified way. The greatest advances of the past have been steps toward this goal: the unification of terrestrial and celestial mechanics by Isaac Newton in the 17th century; of optics with the theories of electricity and magnetism by James Clerk Maxwell in the 19th century; of space-time geometry and the theory of gravitation by Albert Einstein in the years 1905 to 1916; and of chemistry and atomic physics through the advent of quantum mechanics in the 1920s [*see illustrations on pages 70 and 71*].

Einstein devoted the last 30 years of his life to an unsuccessful search for a "unified field theory," which would unite general relativity, his own theory of space-time and gravitation, with Maxwell's theory of electromagnetism. Progress toward unification has been made more recently, but in a different direction. Our current theory of elementary particles and forces, known as the Standard Model of particle physics, has achieved a unification of electromagnetism with the weak interactions, the forces responsible for the change of neutrons and protons into each other in radioactive processes and in the stars. The Standard Model also gives a separate but similar description of the strong interactions, the forces that hold quarks together inside protons and neutrons and hold protons and neutrons together inside atomic nuclei.

We have ideas about how the theory of strong interactions can be unified

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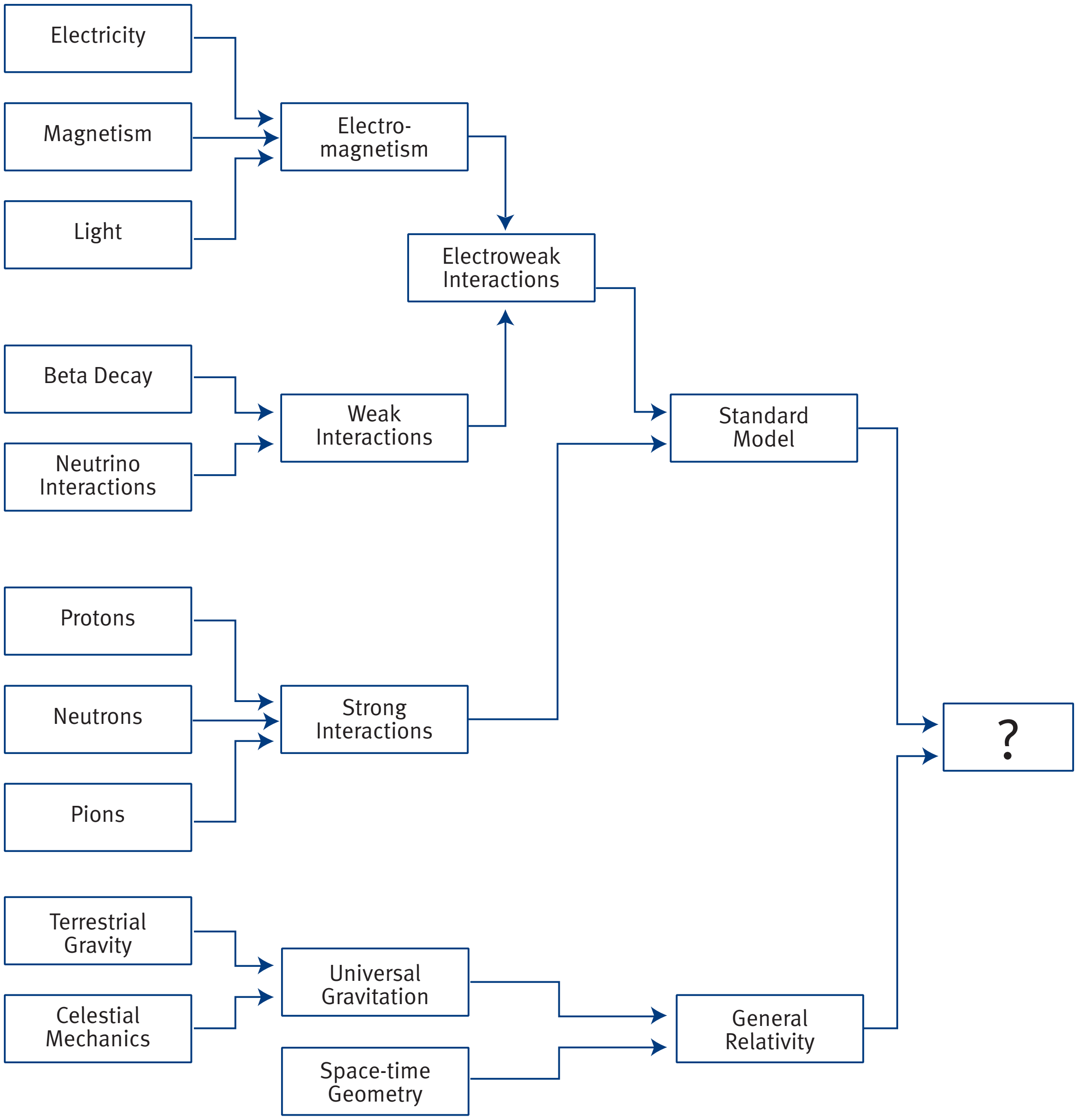
**The quantum nature of space and time must be dealt with in a unified theory. At the shortest distance scales, space may be replaced by a continually reconnecting structure of strings and membranes—or by something stranger still.**

Unification of disparate phenomena within one theory has long been a central theme of physics. The Standard Model of particle physics successfully describes three (electromagnetism, weak and strong interactions) of the four known forces of nature but remains to be united definitively with general relativity, which governs the force of gravity and the nature of space and time.

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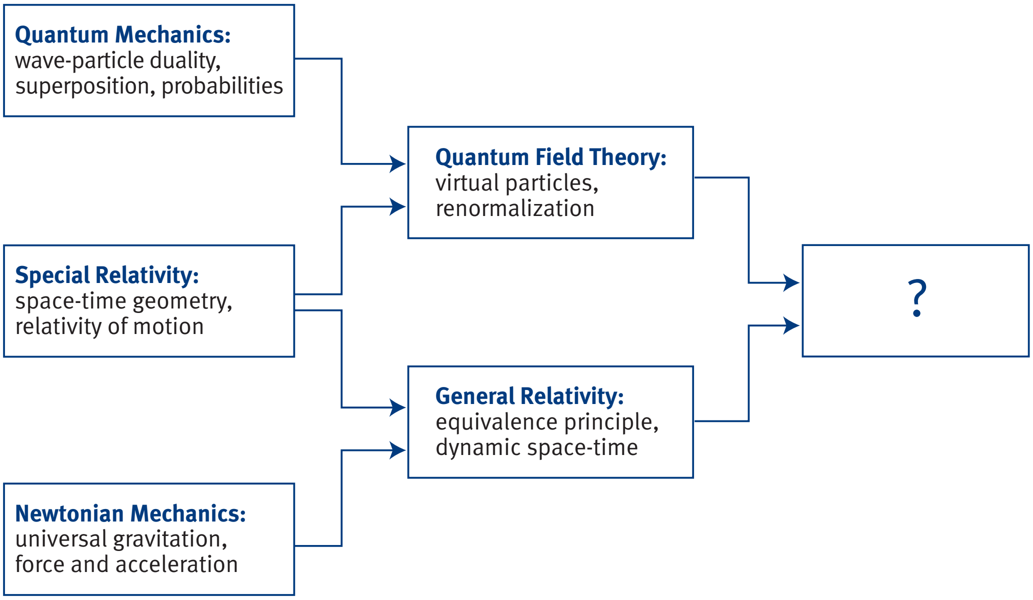
with the theory of weak and electromagnetic interactions (often called Grand Unification), but this may only work if gravity is included, which presents grave difficulties. We suspect that the apparent differences among these forces have been brought about by events in the very early history of the big bang, but we cannot follow the details of cosmic history at those early times without a better theory of gravitation and the other forces. There is a chance the work of unification will be completed by 2050, but about that we cannot be confident.

## Quantum Fields

The Standard Model is a quantum field theory. Its basic ingredients are fields, including the electric and magnetic fields of 19th-century electrodynamics. Little ripples in these fields carry energy and momentum from place to place, and quantum mechanics tells us that these ripples come in bundles, or quanta, that are recognized in the laboratory as elementary particles. For instance, the quantum of the electromagnetic field is a particle known as the photon.

The Standard Model includes a field for each type of elementary particle that has been observed in high-energy physics laboratories [*see top illustration on page 72*]. There are the lepton fields: their quanta include the familiar electrons, which make up the outer parts of ordinary atoms, similar heavier particles known as muons and tauons, and related electrically neutral particles known as neutrinos. There are fields for quarks of various types, some of which are bound together in the protons and neutrons that make up the nuclei of ordinary atoms. Forces between these particles are produced by the exchange of photons and similar elementary particles: the $W^+$, $W^-$ and $Z^0$ transmit the weak force, and eight species of gluon produce the strong forces.

These particles exhibit a wide variety of masses that follow no recognizable pattern, with the electron 350,000 times lighter than the heaviest quark, and neutrinos even lighter. The Standard




**The profoundest advances in fundamental physics tend to occur when the principles of different types of theories are reconciled within a single new framework. We do not yet know what guiding principle underlies the unification of quantum field theory, as embodied in the Standard Model, with general relativity.**

Model has no mechanism that would account for any of these masses, unless we supplement it by adding additional fields, of a type known as scalar fields. The word “scalar” means that these fields do not carry a sense of direction, unlike the electric and magnetic fields and the other fields of the Standard Model. This opens up the possibility that these scalar fields can pervade all space without contradicting one of the best established principles of physics, that space looks the same in all directions. (In contrast, if, for example, there were a significant magnetic field everywhere in space, then we could identify a preferred direction by using an ordinary compass.) The interaction of the other fields of the Standard Model with the all-pervasive scalar fields is believed to give the particles of the Standard Model their masses.

### Beyond the Top

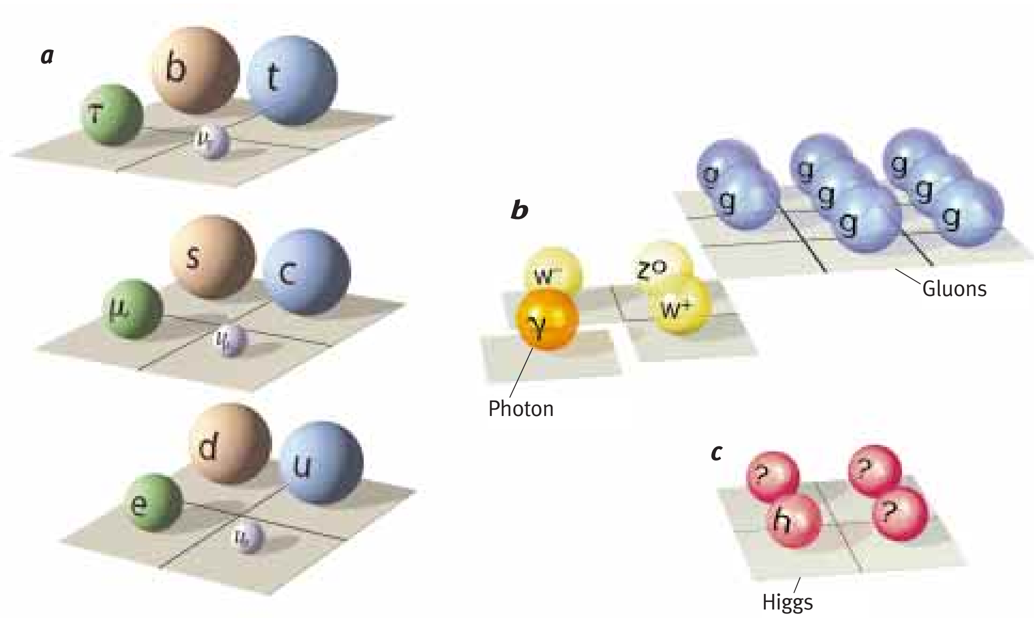
To complete the Standard Model, we need to confirm the existence of these scalar fields and find out how many types there are. This is a matter of discovering new elementary particles, often called Higgs particles, that can be recognized as the quanta of these fields. We have every reason to expect that this task will be accomplished before 2020, when the accelerator called the Large Hadron Collider at CERN, the European laboratory for particle physics near Geneva, will have been operating for over a decade.

The very least new thing that will be discovered is a single electrically neutral scalar particle. It would be a disaster if this were all that were discovered by 2020, though, because it would leave us without a clue to the solution of a formidable puzzle regarding the characteristic energies encountered in physics, known as the *hierarchy problem*.

The heaviest known particle of the Standard Model is the top quark, with a mass equivalent to an energy of 175 gigaelectron volts (GeV). (One GeV is a little more than the energy contained in a proton mass.) [See “The Discovery of the Top Quark,” by Tony M. Liss and Paul L. Tipton; Scientific American, September 1997.] The not yet discovered Higgs particles are expected to have similar masses, from 100 to several hundred GeV. But there is evidence of a much larger scale of masses that will appear in equations of the not yet formulated unified theory. The gluon, *W*, *Z* and photon fields of the Standard Model have interactions of rather different strengths with the other fields of this model; that is why the forces produced by exchange of gluons are about 100 times stronger than the others under ordinary conditions. Gravitation is vastly weaker: the gravitational force between the electron and proton in the hydrogen atom is about $10^{-39}$ the strength of the electric force.

But all these interaction strengths depend on the energy at which they are measured [*see top illustration on page 73*]. It is striking that when the interactions of the fields of the Standard Model are extrapolated, they all become equal to one another at an energy of a little more than $10^{16}$ GeV, and the force of gravitation has the same strength at an energy not much higher, around $10^{18}$ GeV. (Refinements to the theory of gravitation have been suggested that would even bring the strength of gravitation into equality with the other forces at about $10^{16}$ GeV.) We are used to some pretty big mass ratios in particle physics, like the 350,000 to 1 ratio of the top quark to the electron mass, but this is nothing compared with the enormous ratio of the fundamental unification energy scale of $10^{16}$ GeV (or perhaps $10^{18}$ GeV) to the energy scale of about 100 GeV that is typical of the Standard Model

**How can we get the ideas we need** to describe a realm where all intuitions derived from life in space-time become inapplicable?



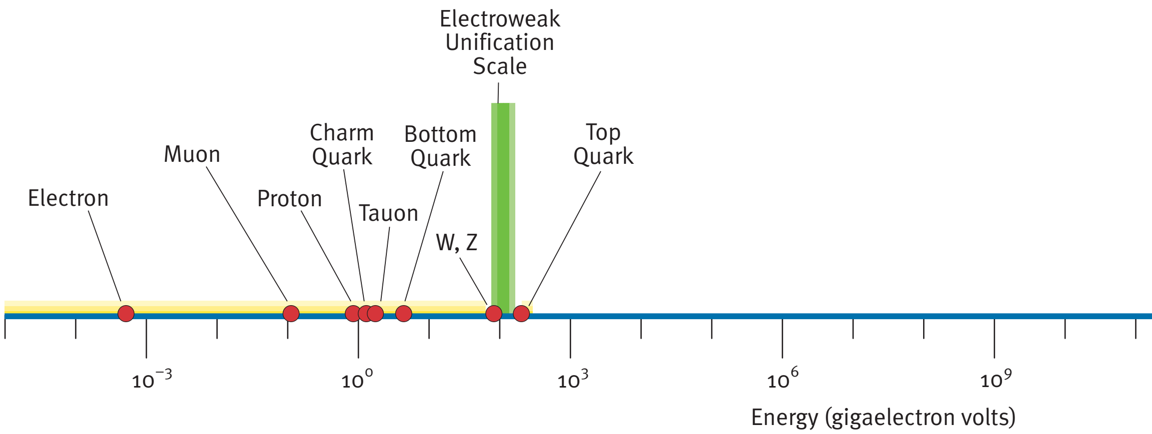

**The Standard Model of particle physics describes each particle of matter and each force with a quantum field. The fundamental particles of matter are fermions and come in three generations (*a*). Each generation of particles follows the same pattern of properties. The fundamental forces are caused by bosons (*b*), which are organized according to three closely related symmetries. In addition, one or more Higgs particles or fields (*c*) generate the masses of the other fields.**

SLIM FILMS

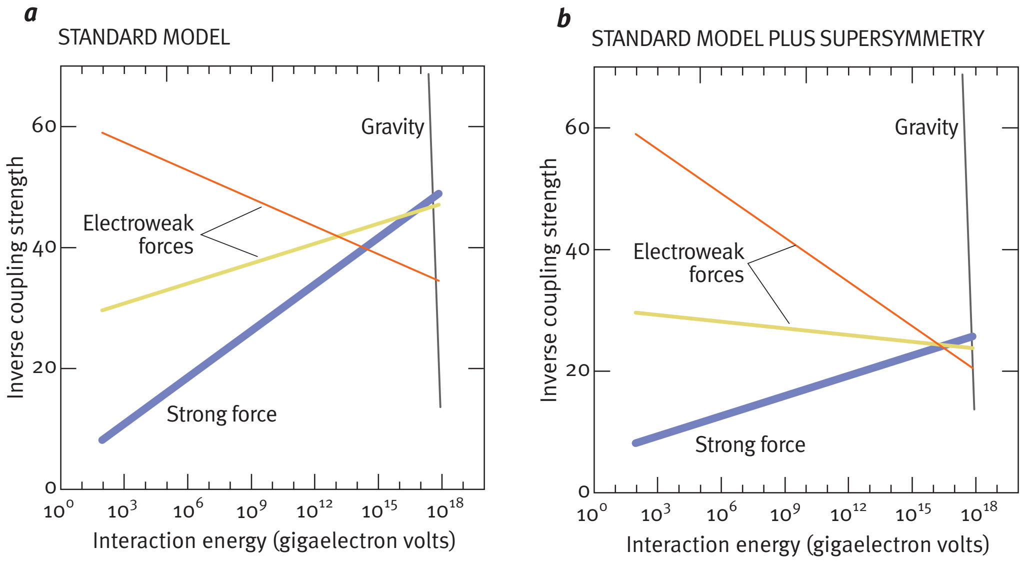
[*see illustration below*]. The crux of the hierarchy problem is to understand this huge ratio, this vast jump from one level to the next in the hierarchy of energy scales, and to understand it not just by adjusting the constants in our theories to make the ratio come out right but as a natural consequence of fundamental principles.

Theorists have proposed several interesting ideas for a natural solution to the hierarchy problem, incorporating a new symmetry principle known as supersymmetry (which also improves the accuracy with which the interaction strengths converge at $10^{16}$ GeV), or new strong forces known as technicolor, or both [*see illustration on page 74*]. All these theories contain additional forces that are unified with the strong, weak and electromagnetic forces at an energy of about $10^{16}$ GeV. The new forces become strong at some energy far below $10^{16}$ GeV, but we cannot observe them directly, because they do not act on the known particles of the Standard Model. Instead they act on other particles that are too massive to be created in our laboratories. These "very heavy" particles are nonetheless much lighter than $10^{16}$ GeV because they acquire their mass from the new forces, which are strong only far below $10^{16}$ GeV. In this picture, the known particles of the Standard Model would interact with the very heavy particles, and their masses would arise as a secondary effect of this relatively weak interaction. This mechanism would solve the hierarchy problem, making the known particles lighter than the very heavy particles, which are themselves much lighter than $10^{16}$ GeV.

All these ideas share another common feature: they require the existence of a zoo of new particles with masses not much larger than 1,000 GeV. If there is any truth to these ideas, then these particles should be discovered before 2020 at the Large Hadron Collider, and some of them may even show up before then at Fermilab or CERN, although it may take further decades and new accelerators to explore their properties fully. When these particles have been discovered and their properties measured, we will be able to tell whether any of them would have survived the early moments of the big bang and could now furnish the "dark matter" in intergalactic space that is




**The hierarchy problem is a measure of our ignorance. Experiments (*yellow band*) have probed up to an energy of about 200 GeV and have revealed an assortment of particle masses (*red*) and interaction energy scales (*green*) that are remarkably well described by the Standard Model. The puzzle is the vast gap to two further energy scales, that of strong-electroweak unification near $10^{16}$ GeV and the Planck scale, characteristic of quantum gravity, around $10^{18}$ GeV.**




**Theoretical extrapolation shows that the three Standard Model forces (the strong force and the unified weak and electromagnetic forces) have roughly equal strength at very high energy (*a*), and the equality is improved by allowing for supersymmetry (*b*). Curve thickness indicates approximate uncertainty in the coupling strengths.**

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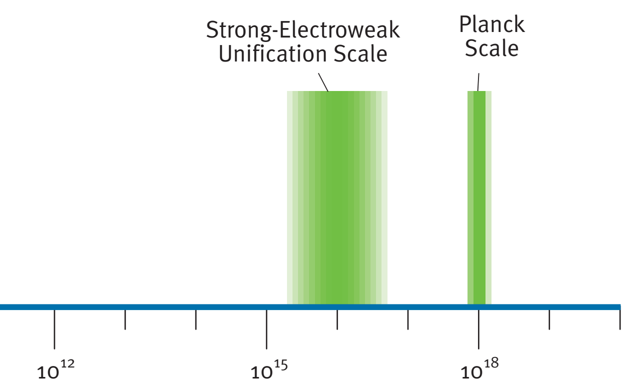
thought to make up most of the present mass of the universe. At any rate, it seems likely that by 2050 we will understand the reason for the enormous ratio of energy scales encountered in nature.

What then? There is virtually no chance that we will be able to do experiments involving processes at particle energies like $10^{16}$ GeV. With present technology the diameter of an accelerator is proportional to the energy given to the accelerated particles. To accelerate particles to an energy of $10^{16}$ GeV would require an accelerator a few light-years across. Even if someone found some other way to concentrate macroscopic amounts of energy on a single particle, the rates of interesting processes at these energies would be too slow to yield useful information. But even though we cannot study processes at energies like $10^{16}$ GeV directly, there is a very good chance that these processes produce effects at accessible energies that can be recognized experimentally because they go beyond anything allowed by the Standard Model.

The Standard Model is a quantum field theory of a special kind, one that is "renormalizable." This term goes back to the 1940s, when physicists were learning how to use the first quantum field theories to calculate small shifts of atomic energy levels. They found that calculations using quantum field theory kept producing infinite quantities, a situation that usually means a theory is badly flawed or is being pushed beyond its limits of validity. In time, they found a way to deal with the infinite quantities by absorbing them into a redefinition, or "renormalization," of just a few physical constants, such as the charge and mass of the electron. (The minimum version of the Standard Model, with just one scalar particle, has 18 of these constants.) Theories in which this procedure worked were called renormalizable and had a simpler structure than nonrenormalizable theories.




### Suppressed Interactions

It is this simple renormalizable structure of the Standard Model that has let us derive specific quantitative predictions for experimental results, predictions whose success has confirmed the validity of the theory. In particular, the principle of renormalizability, together with various symmetry principles of the Standard Model, rules out unobserved processes such as the decay of isolated protons and forbids the neutrinos from having masses. Physicists commonly used to believe that for a quantum field theory to have any validity, it had to be renormalizable. This requirement was a powerful guide to theorists in formulating the Standard Model. It was terribly disturbing that it seemed impossible, for fundamental reasons, to formulate a renormalizable quantum field theory of gravitation.

Today our perspective has changed. Particle physics theories look different depending on the energy of the processes and reactions being considered. Forces produced by exchange of a very massive particle will typically be extremely weak at energies that are low compared with that mass.

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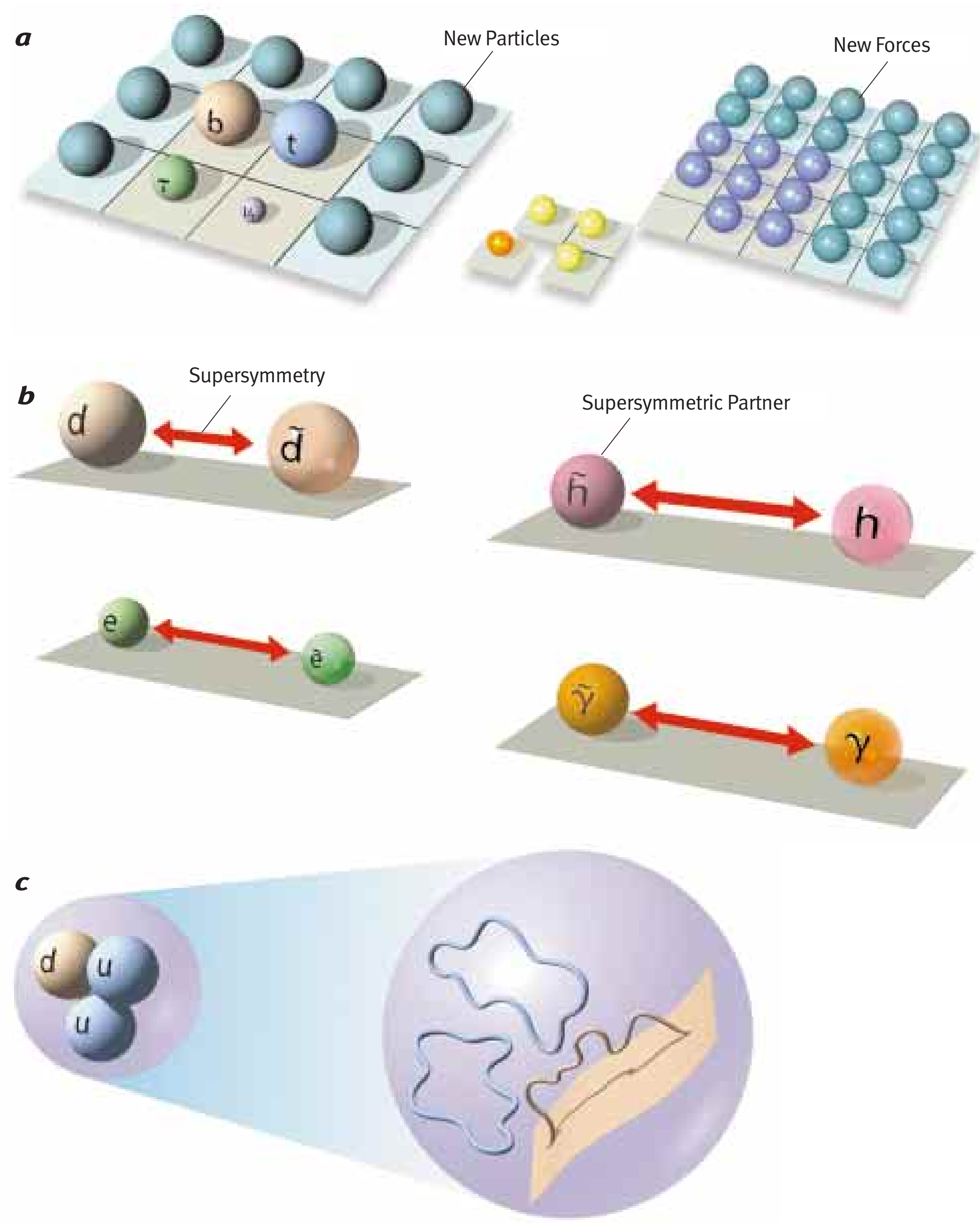
What comes next? There are several possibilities for the unified physics that lies beyond the Standard Model. Technicolor models (*a*) introduce new interactions analogous to the "color" force that binds quarks. Accompanying the interactions are new generations of particles unlike the three known generations. Supersymmetry (*b*) relates fermions to bosons and adds the supersymmetric partners of each known particle to the model. M-theory and string theory (*c*) recast the entire model in terms of new entities such as tiny strings, loops and membranes that behave like particles at low energies.




Other effects can be similarly suppressed, so that at low energies one has what is known as an effective field theory, in which these interactions are negligible. Theorists have realized that any fundamental quantum theory that is consistent with the special theory of relativity will look like a renormalizable quantum field theory at low energies. But although the infinities are still canceled, these effective theories do not have the simple structure of theories that are renormalizable in the classic sense. Additional complicated interactions are present; instead of being completely excluded, they are just highly suppressed below some characteristic energy scale.

Gravitation itself is just such a suppressed nonrenormalizable interaction. It is from its strength (or rather weakness) at low energies that we infer that its fundamental energy scale is roughly $10^{18}$ GeV. Another suppressed nonrenormalizable interaction would make the proton unstable, with a half-life in the range of $10^{31}$ to $10^{34}$ years, which might be too slow to be observed even by 2050 [see my article "The Decay of the Proton"; Scientific American, June 1981]. Yet another suppressed nonrenormalizable interaction would give the neutrinos tiny masses, about $10^{-11}$ GeV. There is already some evidence for neutrino masses of this order; this should be settled well before 2050 [see "Detecting Massive Neutrinos," by Edward Kearns, Takaaki Kajita and Yoji Totsuka; Scientific American, August 1999].

Observations of this kind will yield valuable clues to the unified theory of all forces, but the discovery of this theory will probably not be possible without radically new ideas. Some promising ones are already in circulation. There are five different theories of tiny one-dimensional entities known as strings, which in their different modes of vibration appear at low energy as various kinds of particles and apparently furnish perfectly finite theories of gravitation and other forces in 10 space-time dimensions. Of course, we do not live in 10 dimensions, but it is plausible that six of these dimensions could be rolled up so tightly that they could not be observed in processes at energies below $10^{16}$ GeV per particle. Evidence has appeared in the past few years that these five string theories (and also a quantum field theory in 11 dimensions) are all versions of a single fundamental theory (sometimes called M-theory) that apply under different approximations [see "The Theory Formerly Known as Strings," by Michael J. Duff; SCIENTIFIC AMERICAN, February 1998]. But no one knows how to write down the equations of this theory.

### Outside of Space-time

Two great obstacles stand in the way of this task. One is that we do not know what physical principles govern the fundamental theory. In developing general relativity, Einstein was guided by a principle he had inferred from the known properties of gravitation, the principle of the equivalence of gravitational forces to inertial effects such as centrifugal force. The development of the Standard Model was guided by a principle known as gauge symmetry, a generalization of the well-known property of electricity that it is only differences of voltages that matter, not voltages themselves.

But we have not discovered any fundamental principle that governs M-theory. The various approximations to this theory look like string or field theories in space-times of different dimensionalities, but it seems probable that the fundamental theory is not to be formulated in space-time at all. Quantum field theory is powerfully constrained by principles concerning the nature of four-dimensional space-time that are incorporated in the special theory of relativity. How can we get the ideas we need to formulate a truly fundamental theory, when this theory is to describe a realm where all intuitions derived from life in space-time become inapplicable?

The other obstacle is that even if we were able to formulate a fundamental theory, we might not know how to use it to make predictions that could confirm its validity. Most of the successful predictions of the Standard Model have been based on a method of calculation known as perturbation theory. In quantum mechanics the rates of physical processes are given by sums over all possible sequences of intermediate steps by which the process may occur. Using perturbation theory, one first considers only the simplest intermediate steps, then the next simplest, and so on. This works only if increasingly complicated intermediate steps make decreasingly large contributions to the rate, which is usually the case if the forces involved are sufficiently weak. Sometimes a theory with very strong forces is equivalent to another theory with very weak forces, which can be solved by the methods of perturbation theory. This seems to be true of some pairs of the five string theories in 10 dimensions and the field theory in 11 dimensions mentioned earlier. Unfortunately, the forces of the fundamental theory are probably neither very strong nor very weak, ruling out any use of perturbation theory.

### Recognizing the Answer

It is impossible to say when these problems will be overcome. They may be solved in a preprint put out tomorrow by some young theorist. They may not be solved by 2050, or even 2150. But when they are solved, even though we cannot do experiments at $10^{16}$ GeV or look into higher dimensions, we will not have any trouble in recognizing the truth of the fundamental unified theory. The test will be whether the theory successfully accounts for the measured values of the physical constants of the Standard Model, along with whatever other effects beyond the Standard Model may have been discovered by then.

It is possible that when we finally understand how particles and forces behave at energies up to $10^{18}$ GeV, we will just find new mysteries, with a final unification as far away as ever. But I doubt it. There are no hints of any fundamental energy scale beyond $10^{18}$ GeV, and string theory even suggests that higher energies have no meaning.

The discovery of a unified theory that describes nature at all energies will put us in a position to answer the deepest questions of cosmology: Did the expanding cloud of galaxies we call the big bang have a beginning at a definite time in the past? Is our big bang just one episode in a much larger universe in which big and little bangs have been going on eternally? If so, do what we call the constants of nature or even the laws of nature vary from one bang to another?

This will not be the end of physics. It probably won't even help with some of the outstanding problems of today's physics, such as understanding turbulence and high-temperature superconductivity. But it will mark the end of a certain kind of physics: the search for a unified theory that entails all other facts of physical science. SA

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**STEVEN WEINBERG** is head of the Theory Group at the University of Texas at Austin and a member of its physics and astronomy departments. His work in elementary particle physics has been honored with numerous prizes and awards, including the Nobel Prize for Physics in 1979 and the National Medal of Science in 1991. The third volume (*Supersymmetry*) of his treatise *The Quantum Theory of Fields* is due out this month from Cambridge University Press. The second volume (*Modern Applications*) was hailed as being "unmatched by any other book on quantum field theory for its depth, generality and definitive character."

## FURTHER INFORMATION


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