The Higgs Boson

It could give mathematical consistency to the standard model—the theory that describes the interactions of fundamental particles. The search for the elusive particle will require new accelerators

by Martinus J. G. Veltman

The truly fundamental problems of physics can always be explained in simple terms without the help of complicated equations or mathematical arguments. At least this was once told to me by Victor F. Weisskopf, an eminent physicist who often engages in such explanations, and he may very well be right. It certainly holds for a proposed but undiscovered particle called the Higgs boson and the so-called Higgs field associated with it.

The Higgs boson, which is named after Peter W. Higgs of the University of Edinburgh, is the chief missing ingredient in what is now called the standard model of elementary processes: the prevailing theory that describes the basic constituents of matter and the fundamental forces by which they interact. According to the standard model, all matter is made up of quarks and leptons, which interact with one another through four forces: gravity, electromagnetism, the weak force and the strong force. The strong force, for instance, binds quarks together to make protons and neutrons, and the residual strong force binds protons and neutrons together into nuclei. The electromagnetic force binds nuclei and electrons, which are one kind of lepton, into atoms, and the residual electromagnetic force binds atoms into molecules. The weak force is responsible for certain kinds of nuclear decay. The influence of the weak force and the strong force extends only over a short range, no larger than the radius of an atomic nucleus; gravity and electromagnetism have an unlimited range and are therefore the most familiar of the forces.

In spite of all that is known about the standard model, there are reasons to think it is incomplete. That is where the Higgs boson comes in. Specifically, it is held that the Higgs boson gives mathematical consistency to the standard model, making it applicable to energy ranges beyond the capabilities of the current generation of particle accelerators but that may soon be reached by future accelerators. Moreover, the Higgs boson is thought to generate the masses of all the fundamental particles; in a manner of speaking, particles "eat" the Higgs boson to gain weight.

The biggest drawback of the Higgs boson is that so far no evidence of its existence has been found. Instead a fair amount of indirect evidence already suggests that the elusive particle does not exist. Indeed, modern theoretical physics is constantly filling the vacuum with so many contraptions such as the Higgs boson that it is amazing a person can even see the stars on a clear night! Although future accelerators may well find direct evidence of the Higgs boson and show that the motivations for postulating its existence are correct, I believe things will not be so simple. I must point out that this does not mean the entire standard model is wrong. Rather, the standard model is probably only an approximation—albeit a good one—of reality.

Even though the only legitimate reason for introducing the Higgs boson is to make the standard model mathematically consistent, much attention has been given to the conceptually easier proposal that the particle generates the masses of all the fundamental particles. I shall therefore begin with that topic.

Central to an understanding of how the Higgs boson would generate mass is the concept of a field. A field is simply a quantity, such as temperature, defined at every point throughout some region of space and time, such as the surface of a frying pan. In physics the term "field" is usually reserved for such entities as the gravitational field and the electromagnetic field. Fields generally make themselves felt by means of the exchange of a mediating particle; the particle that mediates the electromagnetic field, for example, is the photon, or quantum of light. The mediating particles of the gravitational field, the weak field and the strong field are respectively the graviton (which has not yet been detected), three weak vector bosons, called the W^+, W^- and Z^0 particles, and eight gluons. In a somewhat analogous way the Higgs boson is the mediating particle of the proposed Higgs field.

It is now assumed that there is a constant Higgs field throughout all space, that is, the vacuum of outer space is not empty but contains this constant field. The Higgs field is thought to generate mass by coupling to particles. Depending on the coupling strength, a particle in space has a certain potential energy. By Einstein's famous equation, $E = mc^2$ (energy equals mass multiplied by the square of the speed of light), the coupling energy is equivalent to a mass. The stronger the coupling, the greater the mass.

The way particles are thought to acquire mass in their interactions with the Higgs field is somewhat analogous to the way pieces of blotting paper absorb ink. In such an analogy the pieces of paper represent individual particles and the ink represents energy, or mass. Just as pieces of paper of differing size and thickness soak up varying amounts of ink, different particles "soak up" varying amounts of energy, or mass. The observed mass of a particle depends on the particle's "energy-absorbing" ability and on the strength of the Higgs field in space.

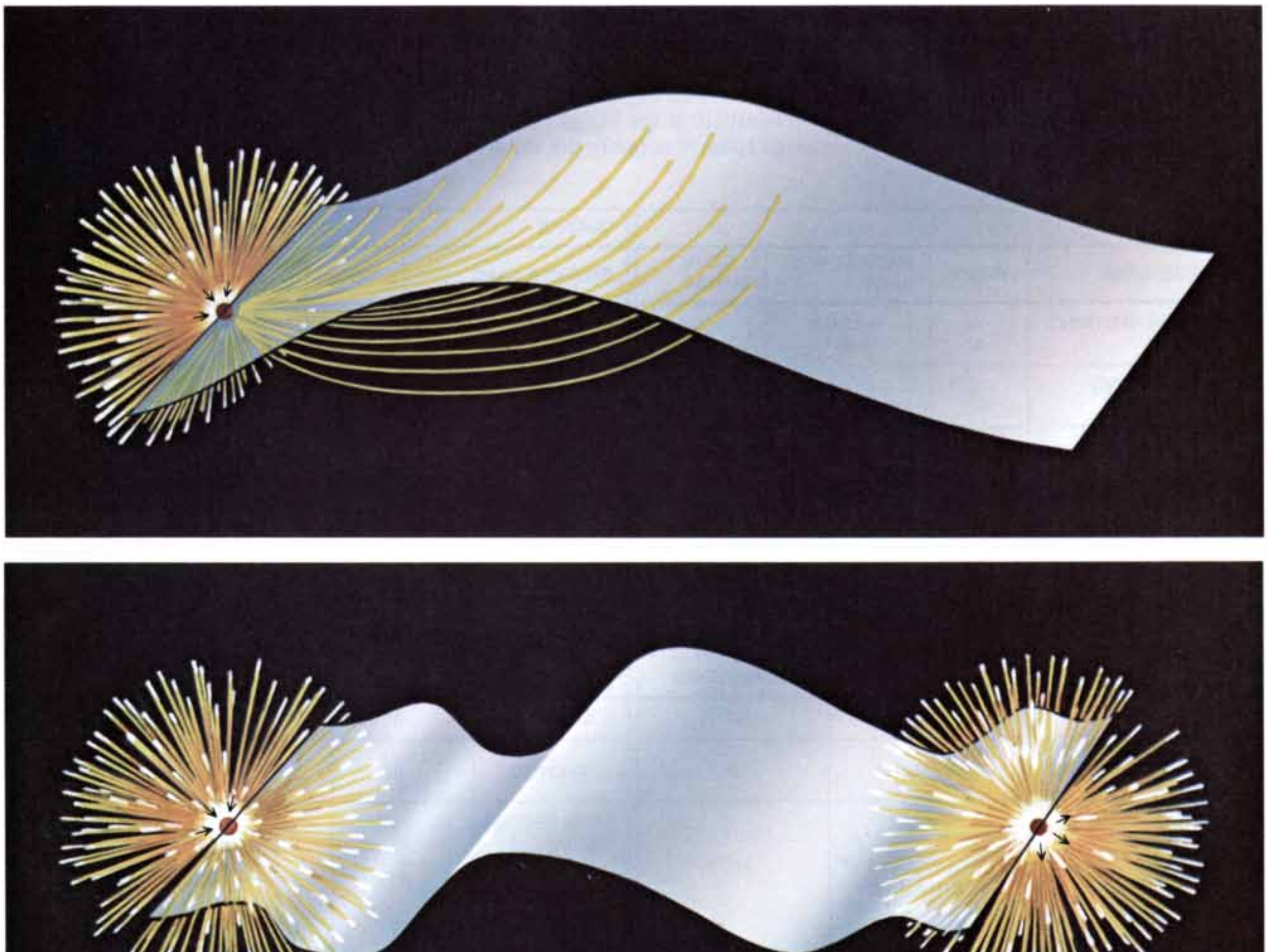
What are the characteristics of the proposed Higgs field? In order to endow particles with mass, the Higgs field, if it exists, would have to assume a uniform, nonzero value even in the vacuum. Moreover, the Higgs field would be a scalar field, which is one of two kinds of field important in describing the interactions of particles. A scalar field is a field in which each point has associated with it a single magnitude, or number. The other important field is a vector field: a field where at each point a vector, or arrow, is drawn. A vector has both a magnitude, which is represented by the length of the arrow, and a direction. The electromagnetic, weak and strong fields are all vector fields. (The gravitational field is a special entity called a tensor field.)

The proposed Higgs field must be a scalar field, because if it were a vector field, the mass of a particle would in general depend on the particle's alignment with the field. Stated in a somewhat oversimplified way, the mass of a person would change if he or she turned around while standing in the same place. In other words, the Higgs field is "spinless."

Because the Higgs field is spinless, the Higgs boson must also be spinless. Spin, as applied to elementary particles, is a quantum-mechanical property roughly equivalent to the classical spin of a rotating ball. Elementary particles can take on only integer (0, 1, 2 and so on) and half-integer (1/2, 3/2 and so on) values of spin. Particles that have integral spin are called bosons and particles that have half-integral spin are called fermions. Bosons and fermions have sharply differing properties, but I shall not delve into that topic here.

The Higgs boson is called a scalar boson because it has a spin of 0. Most other bosons associated with fields are thought to be vector bosons: particles that have a spin of 1. The photon, gluon and W^+, W^- and Z^0 particles, for instance, are spin-1 bosons.

Since vector bosons are typically associated with the fundamental forces of nature and the Higgs boson is a scalar boson, the force by which particles couple to the Higgs field must be a new force. It is introduced explicitly and solely as a mechanism to improve the mathematical consistency of the standard model. The Higgs force behaves mathematically in a similar manner to the recently publicized "fifth force" reported by Ephraim Fischbach of Purdue University. The



MAGNETIC MONOPOLES should exist if the Higgs boson exists. Classically, of course, magnetic monopoles are not found because when a bar magnet is cut in half, two smaller bar magnets are created—not isolated "north" and "south" poles. Magnetic monopoles could, however, be formed by sweeping magnetic field lines under the Higgs "rug" (*top*). The bottom illustration shows a pair of monopoles. Although there have been scattered reports of finding monopoles, none of them has been substantiated to date.

proposed Higgs force is, however, weaker and has a much shorter range than the "fifth force."

The Higgs force is not a universal force, because it couples differently to different particles. Specifically, if a particle is observed to have mass, the strength of the coupling to the Higgs field is assumed to be whatever quantity is necessary to generate precisely that mass. Presumably the Higgs field does not couple to the photon, since experiment shows the photon is massless. But apparently it couples to the W^+, W^- and Z^0 particles, because they do have mass. It should perhaps be noted that particles could have a mass of their own, in addition to what they are thought to acquire from the Higgs field. Curiously, however, in the standard model not a single particle could have a mass of its own without destroying the mathematical completeness of the theory.

From a physical point of view little is gained by proposing that the Higgs boson accounts for mass. It is not known, for example, why the Higgs field should couple more strongly to some particles than it does to others. Nor do investigators understand how the mass of the Higgs boson itself (which is not known) comes about, although it is generally presumed to be dominantly through a self-interaction with the Higgs field. In this sense ignorance about the origin of particle masses is replaced by ignorance about particle-Higgs couplings, and no real knowledge is gained.

Moreover, the introduction of the Higgs boson creates a significant problem with respect to the "holy" field of gravitation. The equivalence of mass and energy implies that the graviton, which couples to anything that carries mass, should couple to anything that carries energy, including the Higgs field. The coupling of the graviton to the Higgs field—ever present in all space—would generate a huge "cosmological constant": it would curve the universe into an object roughly the size of a football. If the Higgs boson is assumed to have roughly the same mass as the weak vector bosons, the energy density of the Higgs field in the vacuum would be 10 trillion times greater than the density of matter in an atomic nucleus. If the earth were compressed to this density, its volume would be approximately 500 cubic centimeters, or a bit more than the size of a soft-drink can. Needless to say, this is contrary to experiment.

The theorists' way out is really something. It is assumed that the "true" vacuum (one without a Higgs field) is curved in a negative sense: it has a cosmological constant equal in magnitude but opposite in sign to the one generated by the Higgs field. The introduction of the Higgs field then flattens out space to make precisely the universe as we know it. This solution is, of course, not very satisfactory, and many ingenious attempts have been made to solve the problem of the huge cosmological constant. None of the attempts has succeeded. If anything, matters have grown worse because theorists keep dumping more particles and fields into the vacuum.

LEPTONS			
PARTICLE NAME	SYMBOL	MASS AT REST (MeV)	ELECTRIC CHARGE
ELECTRON NEUTRINO	ν_e	ABOUT 0	0
ELECTRON	e^-	0.511	−1
MUON NEUTRINO	ν_μ	ABOUT 0	0
MUON	μ^-	106.6	−1
TAU NEUTRINO	ν_τ	LESS THAN 164	0
TAU	τ^-	1,784	−1

QUARKS			
PARTICLE NAME	SYMBOL	MASS AT REST (MeV)	ELECTRIC CHARGE
UP	u	310	+ ⅔
DOWN	d	310	− ⅓
CHARM	c	1,500	+ ⅔
STRANGE	s	505	− ⅓
TOP/TRUTH	t	22,500; HYPOTHETICAL PARTICLE	+ ⅔
BOTTOM/BEAUTY	b	ABOUT 5,000	− ⅓

FORCE	RANGE	STRENGTH AT 10^{-13} CENTIMETER IN COMPARISON WITH STRONG FORCE	CARRIER	MASS AT REST (GeV)	SPIN	ELECTRIC CHARGE	REMARKS
GRAVITY	INFINITE	10^{-38}	GRAVITON	0	2	0	CONJECTURED
ELECTROMAGNETISM	INFINITE	10^{-2}	PHOTON	0	1	0	OBSERVED DIRECTLY
WEAK	LESS THAN 10^{-16} CENTIMETER	10^{-13}	WEAK SECTOR BOSONS: W^+	81	1	+1	OBSERVED DIRECTLY
			W^-	81	1	−1	OBSERVED DIRECTLY
			Z^0	93	1	0	OBSERVED DIRECTLY
STRONG	LESS THAN 10^{-13} CENTIMETER	1	GLUONS	0	1	0	PERMANENTLY CONFINED

STANDARD MODEL of elementary-particle physics holds that there are 12 fundamental constituents of matter (*top*) and four basic forces (*bottom*). The constituents of matter are divided into two groups of six: leptons and quarks. Leptons exist independently, whereas an individual quark has never been isolated. Quarks are always part of larger particles such as protons and neutrons; a proton, for instance, is thought to be made of two up quarks and one down quark. The particles interact with one another by means of the four forces. Each force in turn has a particle associated with it (called a boson) that conveys the force. The Higgs force, if it exists, would be a fifth one, which would be mediated by the Higgs boson. The masses of the fundamental constituents are given in millions of electron volts (MeV) and the masses of the particles that convey the forces are given in billions of electron volts (GeV).

Perhaps somehow the universe became flat from the dynamics of the big-bang explosion, which is believed to have created the universe some 15 to 20 billion years ago.

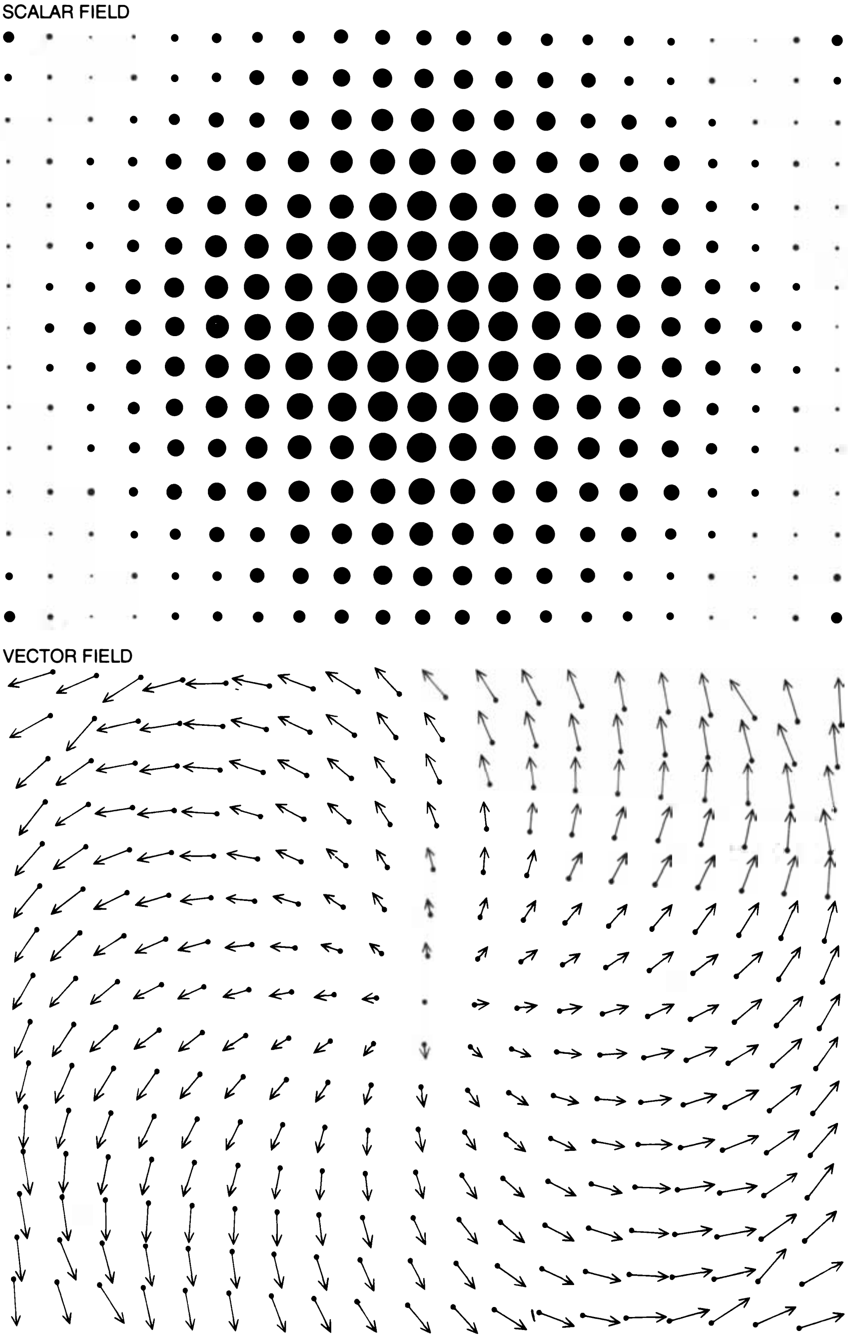
The theory as it stands, with one Higgs field, does not explicitly contradict observation, even if one must accept the incredible disappearance of the cosmological constant. Certain extensions of the theory proposed over the past decade often involve the introduction of additional Higgs fields. Although the arguments for such extensions are often compelling, the phenomena associated with these extra Higgs fields have either never been seen or contradict observed facts.

To account in an elegant way for certain symmetries observed in the strong interactions, for example, a second Higgs field was proposed by Helen R. Quinn of the Stanford Linear Accelerator Center (SLAC) and Roberto Peccei of the Deutsches Elektronen-Synchrotron (DESY, the electron accelerator in Hamburg). The ensuing theory predicted a new and presumably very light particle called the axion. So far, in spite of extensive searches, the axion has not been found. In addition the theory has dramatic cosmological consequences concerning a phenomenon known as "domain walls." In general a domain wall marks where two regions of differing properties meet each other. Domain walls are, for instance, found in permanent magnets, where one region of atoms whose spins are aligned in one direction meets another region of atoms whose spins are aligned in a different direction.

It is believed that certain Higgs fields would have given rise to domain walls in the early universe. When the universe was young, the temperature was extremely hot and no Higgs field is thought to have existed. At some time the universe would have cooled sufficiently to allow a background Higgs field to come into being. Unless the cooling were completely uniform, the Higgs field would quite likely have exhibited different properties from one region in space to the next. To what extent the clash of such regions would result in visible or even violent phenomena depends on detailed properties of the Higgs fields, but one would expect some kind of clash in connection with the suggestive proposal of Quinn and Peccei.

The question is why domain walls between such regions have not been observed. It could mean that there is no Higgs field, or that nature has been careful in its use of the field. Alternatively, the walls could have disappeared early in the history of the universe. This is rather typical: one starts with an excellent argument, drags in a Higgs field and then things go wrong. It certainly inspires little faith in the mechanism altogether.

The introduction of an extra Higgs boson also creates difficulties in a model that is attracting considerable attention called the SU(5) grand unified theory. The goal of unified theories in general is to account for the four forces in terms of one fundamen-



FIELDS are important in describing the interactions of particles with one another. A field is a quantity (such as temperature) defined at every point throughout some region of space and time (such as the surface of a frying pan). Two kinds of fields are scalar fields (*top*) and vector fields (*bottom*). A scalar field is a field in which every point has associated with it a single magnitude, or number, represented here by the area of the dots. A vector field has both a magnitude, which is represented here by the length of an arrow, and a direction, which is represented by the orientation of the arrowhead in space. The electromagnetic, weak and strong fields are examples of vector fields; the Higgs field, if it exists, would be a scalar field. (The gravity field is a special entity called a tensor field.)

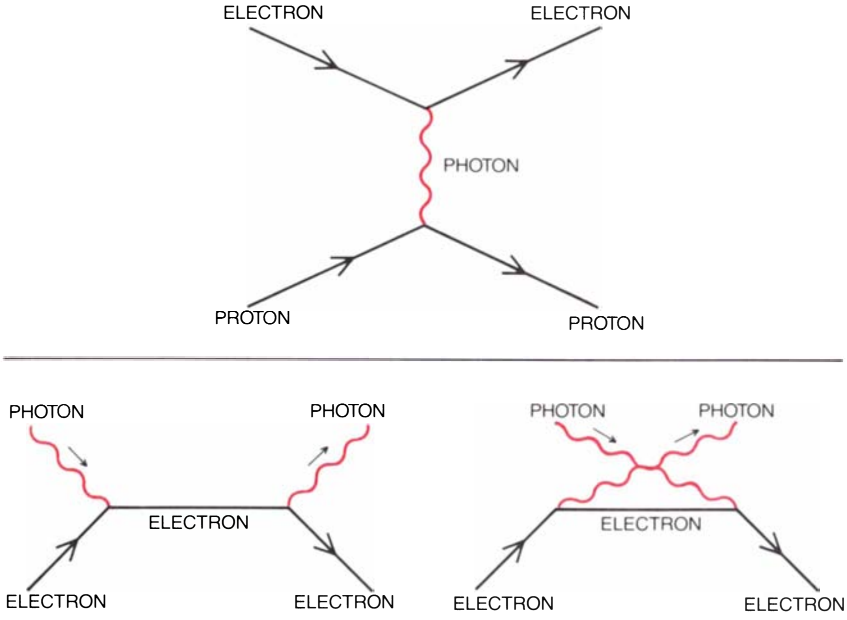
tal force. A step toward achieving that goal was reached over the past two decades with the introduction and verification of the so-called electroweak theory. The theory holds that the electromagnetic force and the weak force are manifestations of the same underlying force: the electroweak force. The electroweak theory was dramatically confirmed in 1983 at CERN, the European laboratory for particle physics, with the detection of the W^+, W^- and Z^0 particles.

The SU(5) grand unified theory seeks to bind the strong force and the electroweak force into one common force; the designation SU(5) refers to the mathematical group of symmetries on which the theory is based. According to SU(5) theory, the strong, weak and electromagnetic forces, which behave quite differently under ordinary circumstances, become indistinguishable when particles interact with an energy of approximately 10^{15} billion electron volts (GeV).

The unification of the strong force with the electroweak force requires the existence of an additional set of vector bosons, whose masses are expected to be several orders of magnitude greater than the masses of the weak vector bosons. Since the new vector bosons are so heavy, they essentially need a Higgs field of their own. In SU(5) theory, therefore, the vacuum contains two Higgs fields that couple with different strengths to different particles.

The most important consequence of the SU(5) theory is that quarks, through the new set of vector bosons, can change into leptons. As a result the proton—that "immortal" conglomeration of three quarks—could decay into lighter particles such as a positron (a type of lepton that can be thought of as a positively charged electron) and a particle called a pion. Given the existence of two Higgs fields, the decay rate can be computed. Experiments done in recent years have not, however, found any such decay [see "The Search for Proton Decay," by J. M. LoSecco, Frederick Reines and Daniel Sinclair; SCIENTIFIC AMERICAN, June, 1985]. It would seem that there is something wrong with the SU(5) theory or the Higgs field or both. I believe the main concepts of the SU(5) theory will survive over the long run.

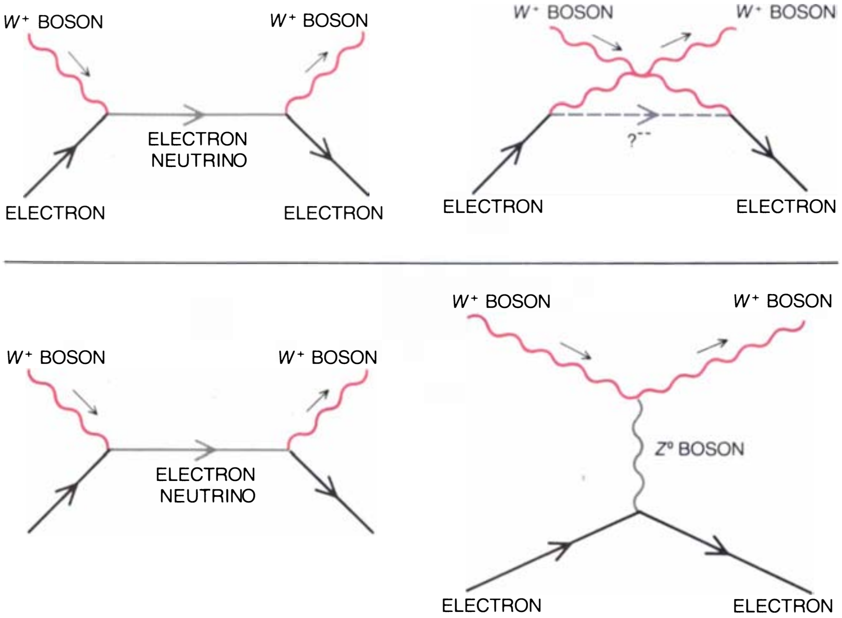
Moreover, if the SU(5) grand unified theory is correct and the Higgs field does exist, magnetic monopoles should have been created in the first 10^{-35} second of the universe. An example of a magnetic monopole is an isolated pole of a bar magnet. (Classically, of course, such objects are not found, because when a bar magnet is cut in half, two smaller bar magnets are created rather than isolated "north" and "south" poles.) Proponents of the SU(5) theory differ over the internal composition of the monopole and over how many monopoles should exist; it is generally agreed that the monopole should have an enormous mass for an elementary particle, perhaps from 10^{16} to 10^{17} times the mass of the proton. Although there have been scattered reports of finding monopoles, none of the reports has been substantiated; nature seems to dislike anything involving Higgs fields. The search for monopoles continues [see "Superheavy Magnetic Monopoles," by Richard A. Carrigan, Jr., and W. Peter Trower; SCIENTIFIC AMERICAN, April, 1982].



FEYNMAN DIAGRAMS are shorthand representations of a well-defined mathematical procedure for determining the probability that one particle will scatter off another. In the top illustration an electron scatters off a proton by exchanging a photon, the carrier of the electromagnetic force. The particles can also scatter off each other by exchanging two or more photons (not shown); such exchanges are statistically less likely, so that the one-photon exchange is a good approximation of reality. A photon can also scatter off an electron. Two diagrams are necessary to approximate such an interaction (*bottom*). In this case it is hard to think of scattering in terms of a force. Instead one must think in terms of elementary processes: the photon can be absorbed or emitted by an electron. There is, however, no fundamental difference between electron-proton scattering and electron-photon scattering; one can think of both types of event as elementary processes.

A further smattering of evidence suggests that nature has been sparing in its use of the Higgs fields—if they have been used at all. As it happens, in the electroweak theory the employment of only the simplest type of Higgs field leads to a relation between the masses of the W bosons and the Z^0 boson. The relation is expressed in terms of a factor called the rho-parameter, which is essentially the ratio of the mass of the W bosons to the mass of the Z^0 boson. (There are correction factors that need not bother us here.) The expected value of the rho-parameter is 1; experimentally it is found to be 1.03, with an estimated error of 5 percent. If there is more than one Higgs field, the rho-parameter can take on virtually any value. Assuming that the agreement between theory and experiment is not accidental, the implication is that only one Higgs field exists.

At this point it becomes necessary to question seriously whether the Higgs boson exists in nature. I mentioned above that the only legitimate reason for postulating the Higgs boson is to make the standard model mathematically consistent. Historically the introduction of the Higgs boson to give such consistency had nothing to do with its introduction to account for mass. The introduction of the Higgs boson to account for mass came out of a "model building" line, in which theories were explicitly constructed to model nature as closely as possible. Workers in this line include Sidney A. Bludman of the University of Pennsylvania, who proposed the bulk of the model containing W bosons, and Sheldon Lee Glashow of Harvard University, who incorporated electromagnetism into Bludman's model. Steven



WEAK VECTOR BOSON, the carrier of the weak force, can scatter off an electron in a way somewhat analogous to the scattering of a photon off an electron (*see bottom of illustration on opposite page*). The interaction at the top right, although mathematically desirable, would require the existence of a doubly charged negative particle. No such particle is known to exist. The problem is resolved by introducing a neutrally charged particle, called the Z^0 boson (*bottom right*). The existence of the boson has been verified.

Weinberg of the University of Texas at Austin, using methods developed by Thomas W. B. Kibble of the Imperial College of Science and Technology in London, replaced the part of the model concerning particle masses with the Higgs mechanism for generating mass. The integration of quarks into the vector-boson theory was achieved by Nicola Cabibbo and Luciano Maiani of the University of Rome, Y. Hara of the University of Tsukuba, Glashow and John Iliopoulos of the École Normale Supérieure in Paris.

All these papers were produced over a rather long period, from 1959 through 1970. In that same period many other suggested attempts at model building were also published, but none of them, including the ones I have cited, drew any attention in the physics community. In fact, most of the authors did not believe their own work either, and they did not pursue the subject any further (with the exception of Glashow and Iliopoulos). The reason for the disbelief was obvious: no one could compute anything. The methods and mathematics known at the time led to nonsensical answers. There was no way to predict experimental results.

While I was considering the body of available evidence in 1968, I decided that Yang-Mills theories (a general class of theories of which the standard model is a specific example) were relevant in understanding weak interactions and that no progress could be made unless the mathematical difficulties were resolved. I therefore started to work on what I call the "mathematical theory" line, in which little attention is paid to the extent theory corresponds to experimental observations. One focuses instead on mathematical content. In this line I was by no means the first investigator. It was started by C. N. Yang and Robert L. Mills of the Brookhaven National Laboratory. Richard Feynman of the California Institute of Technology, L. Faddeev of the University of Leningrad, Bryce S. DeWitt of the University of North Carolina and Stanley Mandelstam of the University of California at Berkeley had already made considerable inroads in this very difficult subject.

I did not finish the work either. The concluding publication was the 1971 thesis of my former student Gerard 't Hooft, who was then at the University of Utrecht. In that period few researchers believed in the subject. More than once I was told politely or not so politely that I was, in the words of Sidney R. Coleman of Harvard University, "sweeping an odd corner of weak interactions." A noted exception was a Russian group, led by E. S. Fradkin of the University of Moscow, that made substantial contributions.

Interestingly enough, the model-building line and the mathematical-theory line proceeded simultaneously for many years with little overlap. I confess that up to 1971 I knew nothing about the introduction of the Higgs boson in the model-building line. For that matter neither did 't Hooft. At one point, in fact, I distinctly remember saying to him that I thought his work had something to do with the Goldstone theorem (a concept that came out of the model-building line). Since neither of us knew the theorem, we stared blankly at each other for a few minutes and then decided not to worry about it. Once again progress arose from "Don't know how," a phrase coined by Weisskopf.

Progress in the mathematical-theory line would ultimately show that the electroweak theory becomes better-behaved mathematically and has more predictive power when the Higgs boson is incorporated into it. Specifically, the Higgs boson makes the theory renormalizable: given a few parameters, one can in principle calculate experimentally observable quantities to any desired precision. A nonrenormalizable theory, in contrast, has no predictive power beyond a certain limit: the theory is incomplete and the solutions to certain problems are nonsense.

I must point out, however, that the electroweak theory can make powerful predictions even without the Higgs boson. The predictions concern the forces among elementary particles. Those forces are investigated in high-energy-physics laboratories by means of scattering experiments. In such experiments beams of high-energy particles are directed at a "target" particle. A beam of electrons might, for instance, be scattered off a proton. By analyzing the scattering pattern of the incident particles, knowledge of the forces can be gleaned.

The electroweak theory successfully predicts the scattering pattern when electrons interact with protons. It also successfully predicts the interactions of electrons with photons, with *W* bosons and with particles called neutrinos. The theory runs into trouble, however, when it tries to predict the interaction of *W* bosons with one another. In particular, the theory indicates that at sufficiently high energies the probability of scattering one *W* boson off another *W* boson is greater than 1. Such a result is clearly nonsense. The statement is analogous to saying that even if a dart thrower is aiming in the opposite direction from a target, he or she will still score a bull's-eye.

It is here that the Higgs boson enters as a savior. The Higgs boson couples

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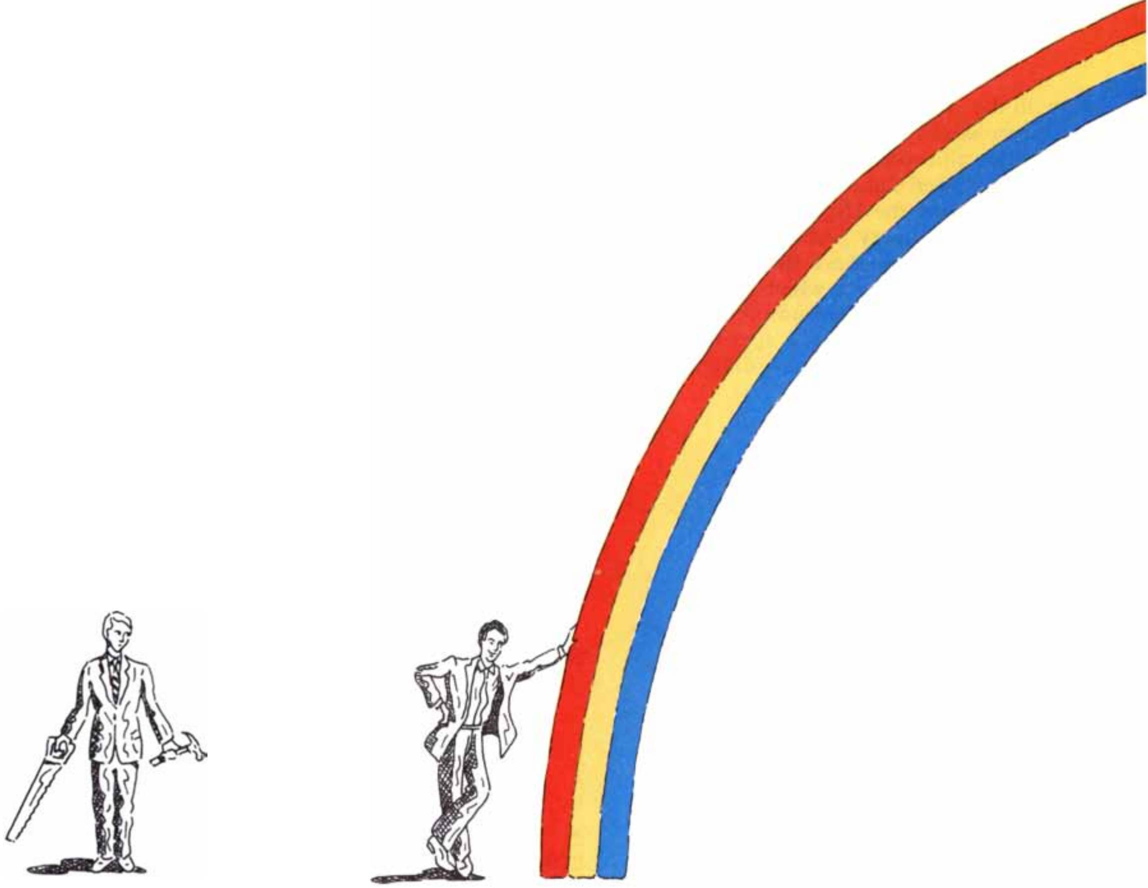

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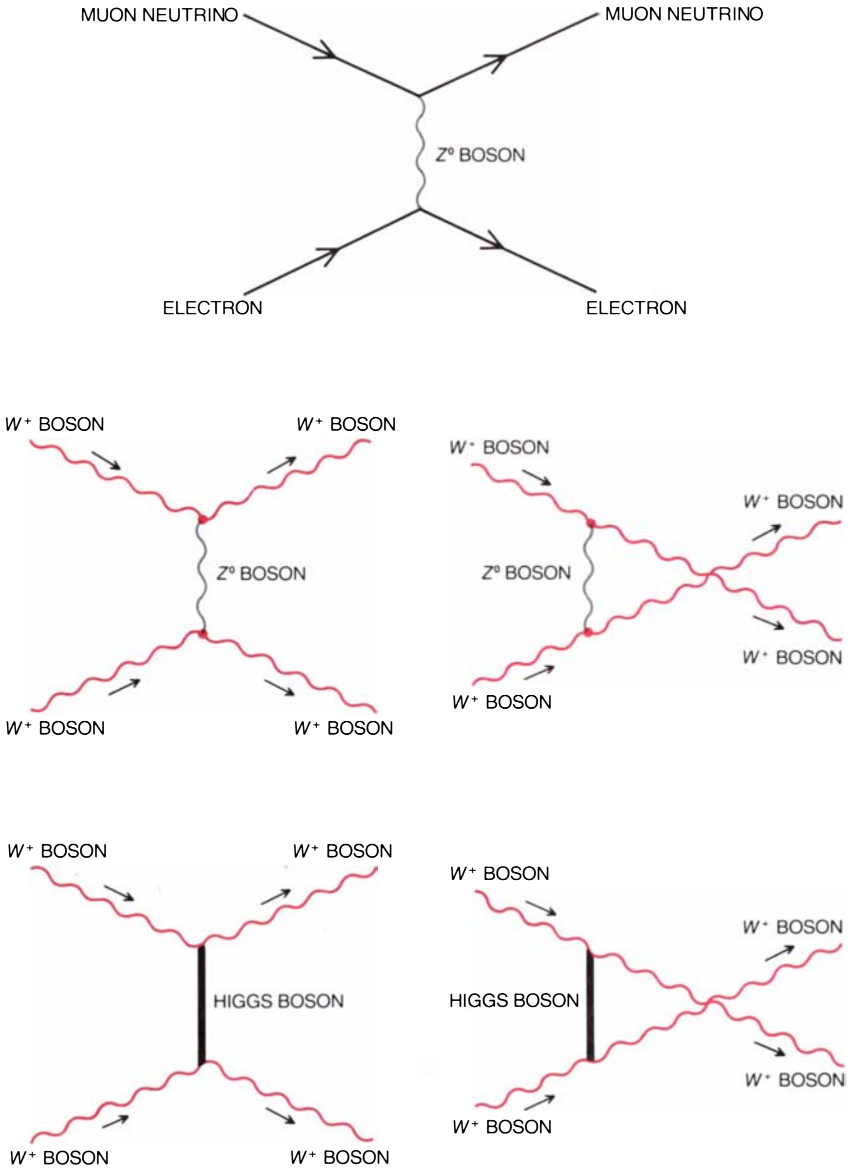
with the *W* bosons in such a way that the probability of scattering falls within allowable bounds: a certain fixed value between 0 and 1. In other words, incorporating the Higgs boson in the electroweak theory "subtracts off" the bad behavior. A more thorough description of the way in which the Higgs boson makes the electroweak theory renormalizable requires a special notation known as Feynman diagrams [*see series of illustrations beginning on page 80 and ending below*].

Armed with the insight that the Higgs boson is necessary to make the electroweak theory renormalizable, it is easy to see how the search for the elusive particle should proceed: weak vector bosons must be scattered off one another at extremely high energies, at or above one trillion electron volts (TeV). The necessary energies could be achieved at the proposed 20-TeV Superconducting Supercollider (SSC), which is currently under consideration in the U.S. [see "The Superconducting Supercollider," by J. David Jackson, Maury Tigner and Stanley Wojcicki; SCIENTIFIC AMERICAN, March]. If the pattern of the scattered particles follows the predictions of the renormalized electroweak theory, then there must be a compensating force, for which the Higgs boson would be the obvious candidate. If the pattern does not follow the prediction, then the weak vector bosons would most likely be interacting through a strong force, and an entire new area of physics would be opened up.



RENORMALIZED ELECTROWEAK THEORY requires the existence of the Higgs boson. A renormalized theory is one that, given a few parameters, can be applied to calculate experimentally observable quantities to any desired precision. A nonrenormalizable theory, in contrast, has no predictive power beyond a certain limit: the theory is incomplete, and the solutions to certain problems are nonsense. Without the Higgs boson the electroweak theory successfully accounts for the scattering of neutrinos off electrons (*top*). The theory runs into trouble, however, when it tries to predict the interaction of *W* bosons with one another (*middle*). Specifically, the theory indicates that at energies above one trillion electron volts (TeV) the probability of scattering one *W* boson off another *W* boson is greater than 1. Such a result is clearly nonsense. The theory is renormalized by introducing the Higgs boson (*bottom*). Plausible predictions can be realized by effectively "subtracting" the set of illustrations at the bottom from the set in the middle.

A difficulty in searching for the Higgs boson is that its mass is virtually unconstrained. As determined by experiment, the mass must be greater than about 5 GeV. Theory presents no clue as to how heavy the Higgs boson could be, except the particle would generate some of the same difficulties it has been designed to solve if its mass were 1 TeV, which is approximately 1,000 times the mass of the proton. At that point theory suggests the weak vector bosons could no longer be viewed as elementary particles; they could be composite structures made of smaller particles.

The notion of a composite structure is, of course, nothing new in the history of physics. At the beginning of the article I mentioned five known layers of structure: molecules, atoms, nuclei, nucleons (protons and neutrons) and quarks and leptons.

In considering the Higgs boson as a composite structure it is only a small step to suppose such "fundamental" particles as quarks and leptons are really composite structures made from still smaller particles [see "The Structure of Quarks and Leptons," by Haim Harari; SCIENTIFIC AMERICAN, April, 1983]. In a sense the notion of a sixth layer of structure, one beyond quarks and leptons, brings me full circle. Traditionally the way to account for free parameters has been to go to a deeper layer of structure. The success of composite models in predicting energy levels of atoms and nuclei suggests that mass could also be predicted by going to a deeper layer of structure. The fact that in the standard model the Higgs boson is responsible for all observed masses implies that, even if in the end there is no such thing as a Higgs boson, there is at least a common source for all masses. Searching for the Higgs boson could ultimately be the same as searching for a deeper structure of elementary particles.