The Number of Families of Matter

How experiments at CERN and SLAC, using electron-positron collisions, showed that there are only three families of fundamental particles in the universe

by Gary J. Feldman and Jack Steinberger

The universe around us consists of three fundamental particles. They are the "up" quark, the "down" quark and the electron. Stars, planets, molecules, atoms—and indeed, ourselves—are built from amalgamations of these three entities. They, together with the neutral and possibly massless partner of the electron, the electron neutrino, constitute the first family of matter.

Nature, however, is not so simple. It provides two other families that are like the first in every respect except in their mass. Why did nature happen to provide three replications of the same pattern of matter? We do not know. Our theories as yet give no indication. Could there be more than three families? Recent experiments have led to the conclusion that there are not.

GARY J. FELDMAN and JACK STEINBERGER were leaders in the effort to determine experimentally the number of families of matter. Feldman received his doctorate from Harvard University in 1971 and spent the following 19 years studying electron-positron annihilation at the Stanford Linear Accelerator Center (SLAC). He was co-leader of the Mark II, the experimental facility of the Stanford Linear Collider (SLC). Last fall he moved to Harvard and began studying proton-antiproton collisions at the Fermilab National Accelerator Laboratory in Batavia, Ill. Steinberger was born in Germany, came to the U.S. as a child and received his doctorate from the University of Chicago in 1948. Since 1968 he has been associated with the European laboratory for particle physics (CERN) near Geneva. Between 1983 and 1990 he headed Aleph, one of four experiments installed at the organization's Large Electron-Positron (LEP) Collider. He shared the 1988 Nobel Prize in Physics for his discovery of the muon neutrino in 1962.

In the spring and summer of 1989, experiments were performed by teams of physicists working at the Stanford Linear Accelerator Center (SLAC) and the European laboratory for particle physics (CERN) near Geneva. The teams used machines of differing designs to cause electrons (e^-) and positrons (e^+) to collide and thus produce quantities of the Z particle (or Z^0, pronounced "zee zero" or "zee naught").

The most massive elementary particle observed, the Z weighs about 100 times as much as a proton and nearly as much as an atom of silver. As we shall see, this mass is merely an average. The Z lifetime is so short that individual Z particles differ slightly in their mass. The spread in the mass values is called a mass width, a quantity that depends on the number of families of matter. Because this width can be measured experimentally, the number of families of matter can be inferred. In this article we describe the experiments by which the families of matter were numbered.

But let us first put this achievement into perspective. The past two and a half decades have witnessed a remarkable systematization of our knowledge of the elementary particles and their interactions with one another. The known particles can be classified either as fermions or as gauge bosons. Fermions are particles of spin 1/2, that is, they have an intrinsic angular momentum of $1/2\hbar$, where $\hbar$ is the Planck unit of action, 10^{-27} erg-second. Fermions may be thought of as the constituents of matter. Gauge bosons are particles of spin 1, or angular momentum $1\hbar$. They can be visualized as the mediators of the forces between the fermions. In addition to their spins, these particles are characterized by their masses and by their various couplings with one another, such as electric charges.

All known couplings, or interactions, can be classified into three types: electromagnetic, weak and strong. (A fourth interaction, gravity, is negligible at the level of elementary particles, so it need not be considered here.) Although the three interactions appear to be different, their mathematical formulation is quite similar. They are all described by theories in which fermions interact by exchanging gauge bosons.

The electromagnetic interaction, as seen in the binding of electrons and nuclei to form atoms, is mediated by the exchange of photons—the electromagnetic gauge bosons. The weak interaction is mediated by the heavy W^+, W^- and Z bosons, whereas the strong interaction is mediated by the eight massless "gluons." The proton, for instance, is composed of three fermion quarks that are bound together by the exchange of gluons.

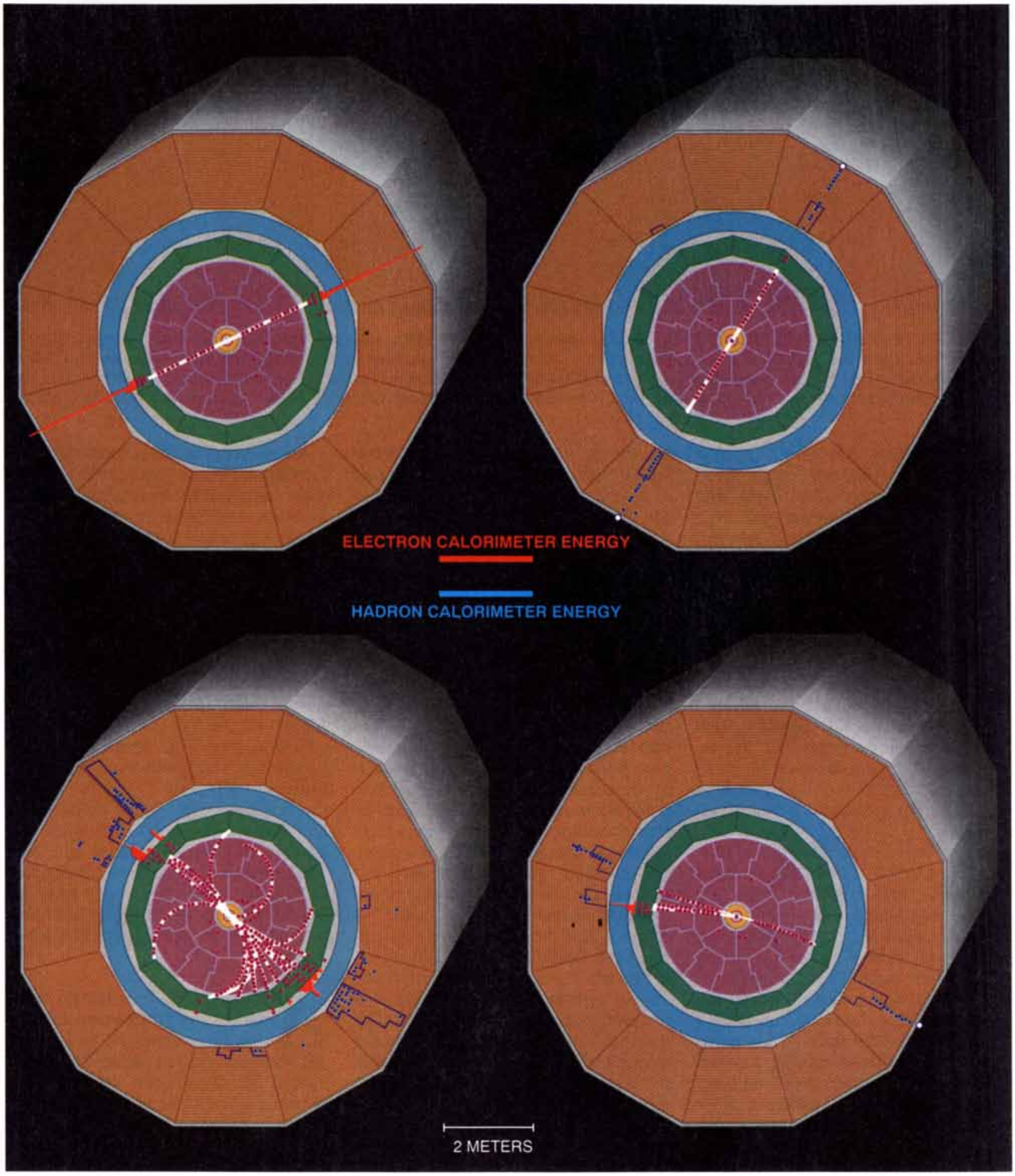
These interactions also describe the creation of particles in high-energy collisions. The conversion of a photon into an electron and a positron serves

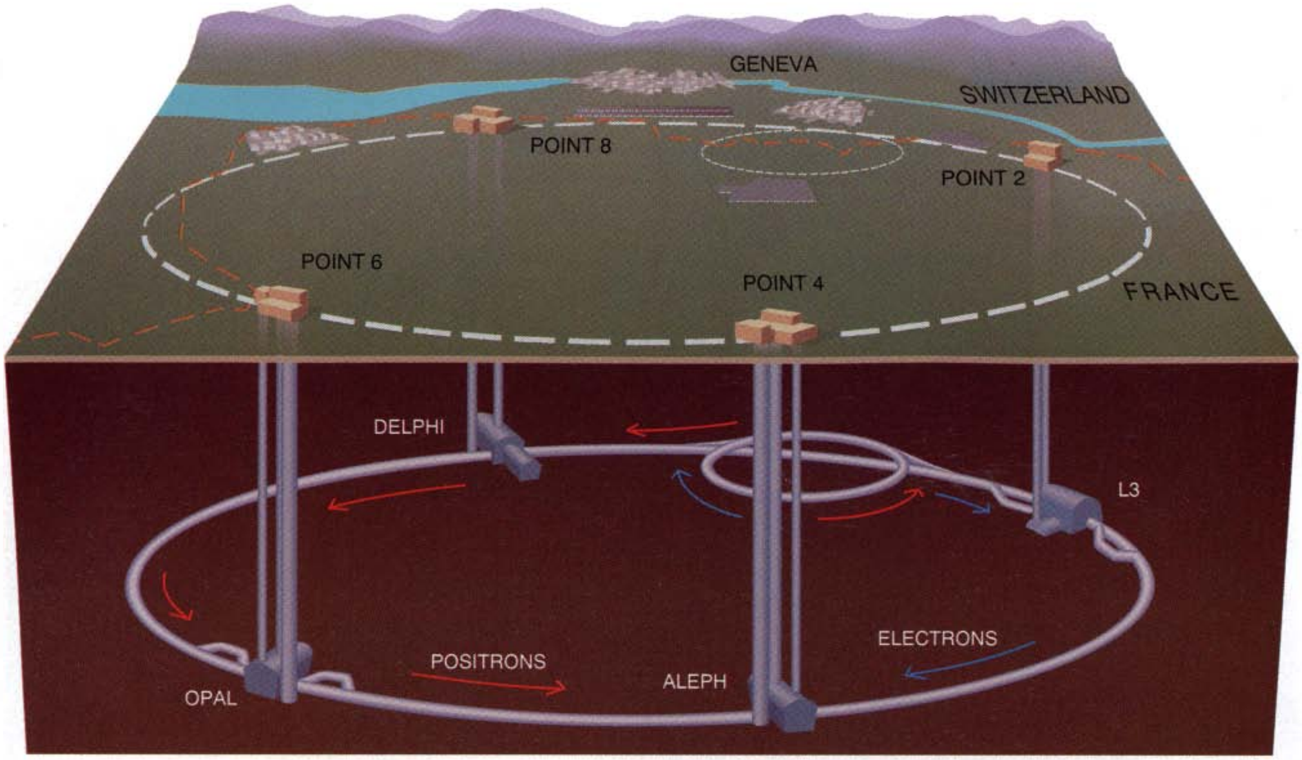
ALEPH DETECTOR, one of four at the Large Electron-Positron (LEP) Collider at CERN near Geneva, recorded these typical decays of Z particles. The cross-sectional diagrams show Z decay products as they traverse the detector. The four decays are (*clockwise, from upper left*) an electron and a positron, which appear as a single line of dots; two muons, which match the electrons' paths but penetrate the outer tracking devices; two tau leptons, one of which has decayed into a muon and two unseen neutrinos, accompanied by another that has decayed into three pions; and two quarks, which form hadron jets. Most Zs decay to quarks. Histograms (*blue and red*) represent particle energies.

as an example. So does the annihilation of an electron colliding with a positron at immensely high energy to produce a *Z* particle.

The evolution of these gauge theories constitutes a strikingly beautiful advance in particle physics. The unification of electromagnetism with the weak interaction was put forward during the years 1968–1971. This "electroweak" theory predicted the neutral weak interaction, discovered at CERN in 1973, and the heavy intermediate bosons W^+, W^- and Z^0, discovered 10 years later, also at CERN [see "Unified Theories of Elementary-Particle Interaction," by Steven Weinberg; SCIENTIFIC AMERICAN, July 1974].

The gauge theory of the strong interaction was advanced in the early 1970s. This theory is called quantum chromodynamics because it explains the strong force by which quarks interact on the basis of their "color." Despite its name, color is an invisible trait. It is to the strong interaction what charge is to the electrical one: a quantity that characterizes the force. But whereas electrodynamic charge has only one state—positive or negative—the color charge has three. Quarks come in red, green and blue; antiquarks come in antired, antigreen and antiblue.





LARGE ELECTRON-POSITRON COLLIDER creates *Z* bosons by bringing electrons and positrons into collision in a storage ring 27 kilometers in circumference. The particles countercirculate in bunches. Magnets confine the two beams to their proper orbits, and radio-frequency power accelerates them to a combined energy near 90 billion electron volts, equivalent to the *Z* mass. The bunches meet head-on 45,000 times a second at points inside the Aleph, Opal, Delphi and L3 detectors.

Together these two gauge theories predict, often with quite high precision, all elementary phenomena that have so far been observed. But their apparent comprehensiveness does not mean that the model is complete and that we can all go home. Gauge theory predicts the existence of the so-called Higgs particle, which is supposed to explain the origin of particle mass. No physicist can be happy until it is spotted or a substitute for it is supplied. Gauge theory also includes a number of arbitrary physical constants, such as the coupling strengths of the interactions and the masses of the particles. A complete theory would explain why these particular values are found in nature.

Among the rules the electroweak theory does provide is one that requires fermions to come in pairs. The electron and electron neutrino are such a pair; they are called leptons because they are relatively light. Another rule is that each particle must have its antiparticle—against the electron is posed the positron; against the electron neutrino, the electron antineutrino. When particles and antiparticles collide, they can annihilate one another, producing secondary particles. Such reactions, as we shall see, underlie the experiments discussed here.

To avoid some subtle disasters in the theory, it is necessary to associate with a lepton pair a corresponding pair of quarks. The electron is the lightest charged lepton, and therefore it is associated with the lightest quarks, the *u* quark (or up quark) and the *d* quark (or down quark). Quarks have not been seen in the free state; they are only found bound to other quarks and antiquarks.

The proton, for example, is composed of two *u* quarks and a *d* quark, whereas the neutron is composed of two *d* quarks and a *u* quark. A complete second family and most of a third have been shown to exist in high-energy experiments. In each case, the particles are much more massive than the corresponding members of the preceding family (the neutrinos form a possible exception). The second family's two leptons are the muon and the muon neutrino; its quarks are the "charm," or *c*, quark, and the "strange," or *s*, quark. The third family's confirmed members are its two leptons—the tau lepton and the tau neutrino—and the "bottom," or *b*, quark. The remaining quark, called the "top," or *t*, quark, is crucial to the electroweak theory. The particle has not been discovered, but we and most other physicists believe it exists and presume it is simply too massive to be brought into existence by today's particle accelerators.

No members of the second and third families are stable (again, with the possible exception of the neutrinos). Their lifetimes range between a millionth and a ten-trillionth of a second, at the end of which they decay into particles of lower mass.

There are two substantial gaps in the electroweak theory's grouping of particles. First, although the theory requires that fermions come in pairs, it does not specify how many pairs constitute a family. There is no reason why each family should not have, in addition to its leptons and quarks, particles of another, still unobserved type. This possibility interests a great number of our colleagues, but so far no new particles have been observed. Second, the theory says nothing about the central question of this article: the number of families of matter. Might there be higher families made up of particles too massive for existing accelerators to produce?

At present, physicists can do nothing but insert observed masses into theories on an ad hoc basis. Some pattern can, however, be discerned [*see illustration on page 73*]. Within a given class of particle (say, a charged lepton or a quark of charge +2/3 or of −1/3), the mass increases considerably in each succeeding family.

The smallest such increase is the nearly 17-fold jump from the muon in the second family to the tau lepton in the third.

Another striking feature is found within families. Leptons are always less massive than quarks, and in every pair of leptons the neutrino is always substantially the less massive particle. In fact, it is uncertain whether neutrinos have any masses at all: experimental evidence merely puts upper limits on the mass each variety can have.

This lightness of neutrinos is essential to the method reported here for counting the number of families of particles. Even if the quark and lepton members of a fourth, fifth or sixth family were far too massive to be created by existing accelerators, the likelihood is nonetheless great that their neutrinos would have little or no mass. Almost certainly the mass of such neutrinos would be less than half the mass of the *Z* boson. If such neutrinos exist, therefore, they would be expected to be among the decay products of the *Z*, the only particle that decays copiously into pairs of neutrinos.

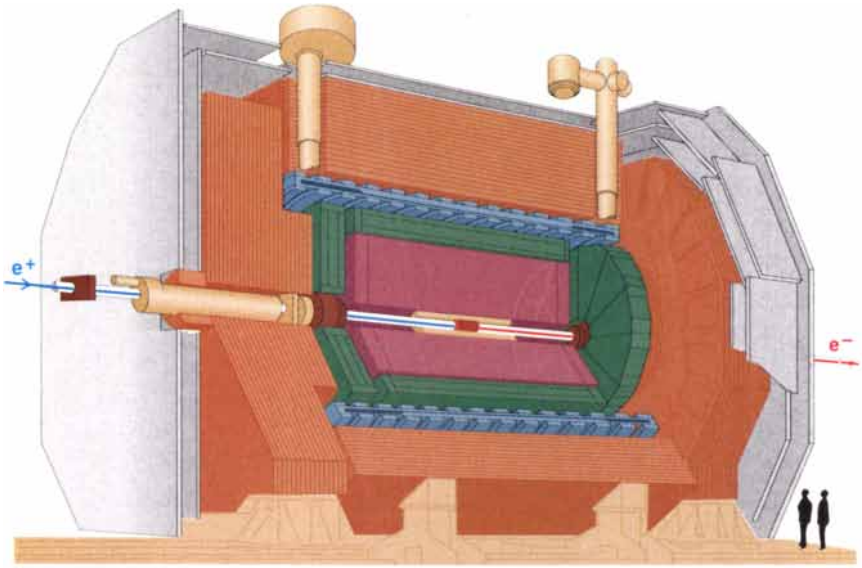
Unfortunately, neutrinos are hard to detect because they do not engage in electromagnetic or strong interactions. They touch matter only through forces that are called "weak," with good reason: most neutrinos pass through the earth without interacting. In the experiments we shall describe, the existence of neutrinos is sought indirectly.

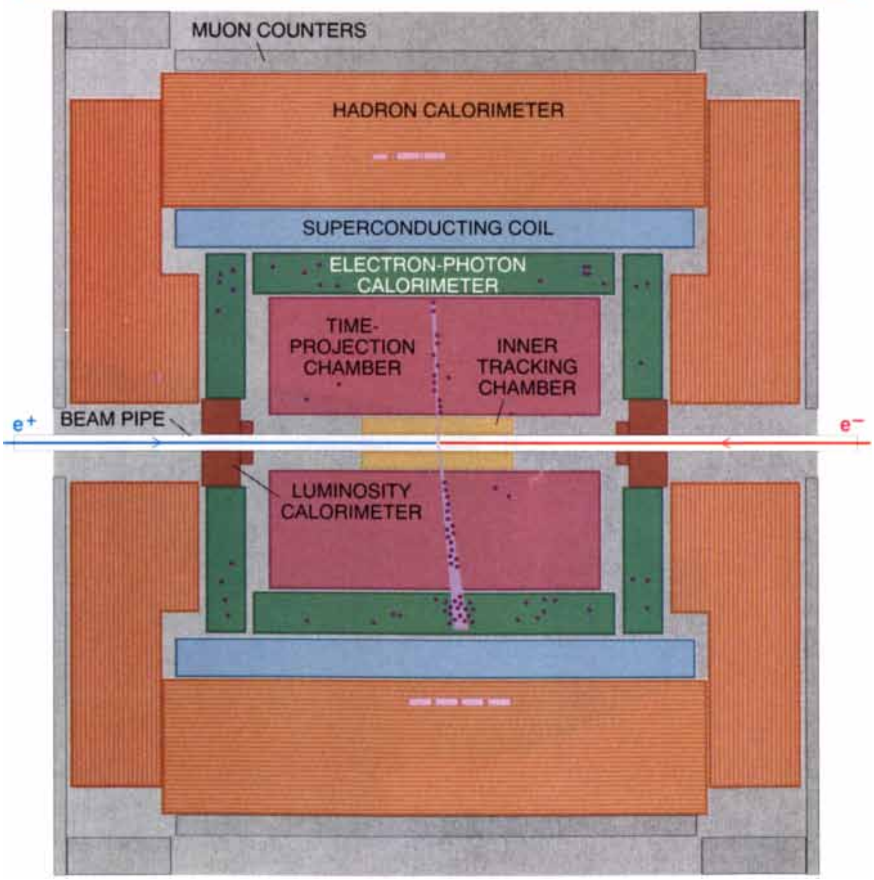
The process begins by creating *Z* particles. The *Z* can be produced by an electron-positron pair whose combined kinetic energies make up the difference between their rest masses (expressed in equivalent energy) and the rest mass of the *Z*. Because these leptons have tiny rest masses, the beams in which they travel must each be raised to the very high energy of 45.5 billion electron volts (eV), about half the *Z* mass.

Now if the *Z* were perfectly stable, the beam energy would have to equal this value precisely to conserve energy and momentum. But such perfect stability is impossible, for if the *Z* can be created from particles, then it must also be free to decay back into them. In fact, the *Z* has many "channels" in which to decay. Each decay channel shortens the life of the *Z*.

Near the beginning of this article, we mentioned that the *Z*'s short life made its mass indeterminate and that the extent of the indeterminacy could be used to number the families of matter. Let us explain why this must be so. One form of the Heisenberg uncertainty principle stipulates that the shorter the duration of a state is, the more uncertain its energy must be. Because the *Z* is short-lived, its energy—or equivalently, its mass—will have a degree of uncertainty. What this means is the following: the mass of any individual *Z* can be measured quite precisely, but different *Z*s will have slightly different masses. If the measured masses of many *Z*s are plotted, the resulting graph has a characteristic bell-like shape. The width of this shape is proportional to the speed at which the *Z* decays.

The shape is measured by varying

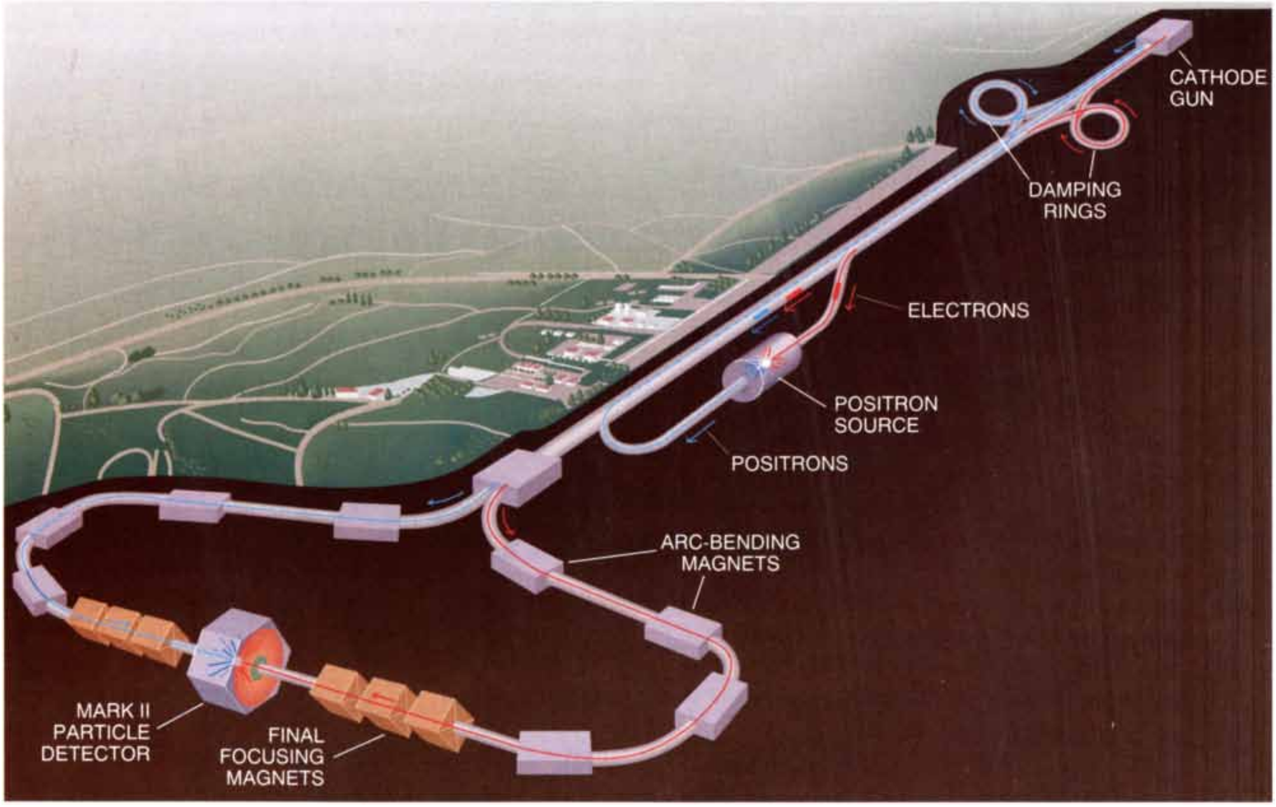




DETECTORS OF ALEPH are arranged in onionlike layers that feed data into computers, which can reconstruct decay events on a screen (*bottom*). Charged particles appear as tracks. The energy of both charged and neutral particles is gauged by calorimeters and graphically displayed. Aleph weighs about 4,000 tons (*top*).

We took a good idea

and built on it.



STANFORD LINEAR COLLIDER speeds positrons and electrons along a three-kilometer straightaway. The injector (*top right*) shoots electrons (*red*) into a damping ring, which condenses them for later focusing. One bunch then enters the straightaway behind a bunch of positrons (*blue*). The two bunches accelerate in tandem before entering separate arcs that focus and direct them to collision in the Mark II detector (*bottom left*). Meanwhile the second bunch of electrons slams into a target, producing positrons (*center*). The positrons are returned to the front, damped and stored.

the collision energy and observing the number of *Z* particles produced. The measurements trace a curve that peaks, or resonates, at a combined beam energy of about 91 billion eV. This point, called the peak cross section, defines the average *Z* mass. The width of the resonance curve defines the particle's mass uncertainty.

The width equals the sum of partial widths contributed by each of the *Z*'s decay channels. The known channels are the decays to particle and antiparticle pairs of all fermions with less than one half the *Z* mass: the three varieties of charged leptons, the five kinds of quarks and the three varieties of neutrinos. If there are other fermions whose masses are less than half the *Z* mass, the *Z* will decay to these as well, and these channels will also contribute to the *Z* width, making it larger.

The present experiments show that such decays to new, charged particles do not occur, so we can be sure that the particles do not exist or that their masses are larger than half the *Z* mass. If, however, higher-mass families do exist, then—as we argued before—their neutrinos would still be expected to have masses much smaller than half the *Z* mass. Therefore, the *Z* would also decay to these channels, and although the neutrinos would not be seen directly in these experiments, these neutrino species would contribute to the *Z* width and so be observable. This is the principle enabling the experiments reported here to number the families of matter.

The electroweak theory predicts the contributions of the known channels to an accuracy of about 1 percent, as follows: for the combined quark channels, 1.74 billion eV; for each charged lepton channel, 83.5 million eV; and for each neutrino channel, 166 million eV.

As the number of assumed neutrinos (and hence families) increases, the predicted *Z* width also increases. The predicted peak cross section, on the other hand, declines by the square of the width [*see illustration on page 75*]. One can consequently deduce the number of families either from the measured width or from the peak cross section. The latter is statistically the more powerful measurement. The establishment of the number of families by direct experimental measurement had to await the production of large numbers of *Z*s by the well-understood process of electron-positron annihilation.

Researchers at CERN attacked the problem by developing the Large Electron-Positron (LEP) Collider, a traditional storage-ring design built on an unprecedented scale [see "The LEP Collider," by Stephen Myers and Emilio Picasso; SCIENTIFIC AMERICAN, July 1990]. The ring, which measures 27 kilometers in circumference, is buried between 50 and 150 meters under the plain that stretches from Geneva to the French part of the Jura Mountains [*see illustration on page 72*]. Resonance cavities accelerate the two beams with radio-frequency power. The beams move in opposite directions through a roughly circular tube. Electromagnets bend the beams around every curve and direct them to collisions in four areas, each of which is provided with a large detector.

The ring design has the advantage of storing the particles indefinitely, so that they can continue to circulate and collide. It has the disadvantage of draining the beams of energy in the form of synchroton radiation, an emission made by any charged particle that is diverted by a magnetic field. Such losses, which at these energies appear as X rays, increase as the fourth power of the beam's energy and are inversely proportional to the ring's radius. Designers can therefore increase the power of their beams by either pouring in more energy or building larger rings, or both. If optimal use is made of resources, the cost of such storage rings scales as the square of beam energy. The LEP is thought to approach the practical economic limit for accelerators of this kind.

At Stanford, the problem of making electrons and positrons collide at high energy was attacked in a novel way in the Stanford Linear Collider (SLC). The electrons and positrons are accelerated in a three-kilometer-long linear accelerator, which had been built for other purposes. They are sent into arcs a kilometer long, brought into collision and then dumped [*see illustration on opposite page*]. The electrons and positrons each lose about 2 percent of their energy because of synchrotron radiation in the arcs, but this loss is tolerable because the particles are not recirculated. A single detector is placed at the point of collision [see "The Stanford Linear Accelerator," by John R. Rees; SCIENTIFIC AMERICAN, October 1989].

The LEP is an efficient device: when the electron and positron beams recirculate, about 45,000 collisions per second occur. The SLC beams collide, at the most, only 120 times per second. Thus, the SLC must increase its efficiency. This task can be accomplished by reducing the beam's cross section to an extremely small area. The smaller the cross section of the area becomes, the more likely it is that an electron will collide head-on with a positron. The SLC has produced beam diameters of four-millionths of a meter, about one fifth the thickness of a human hair.

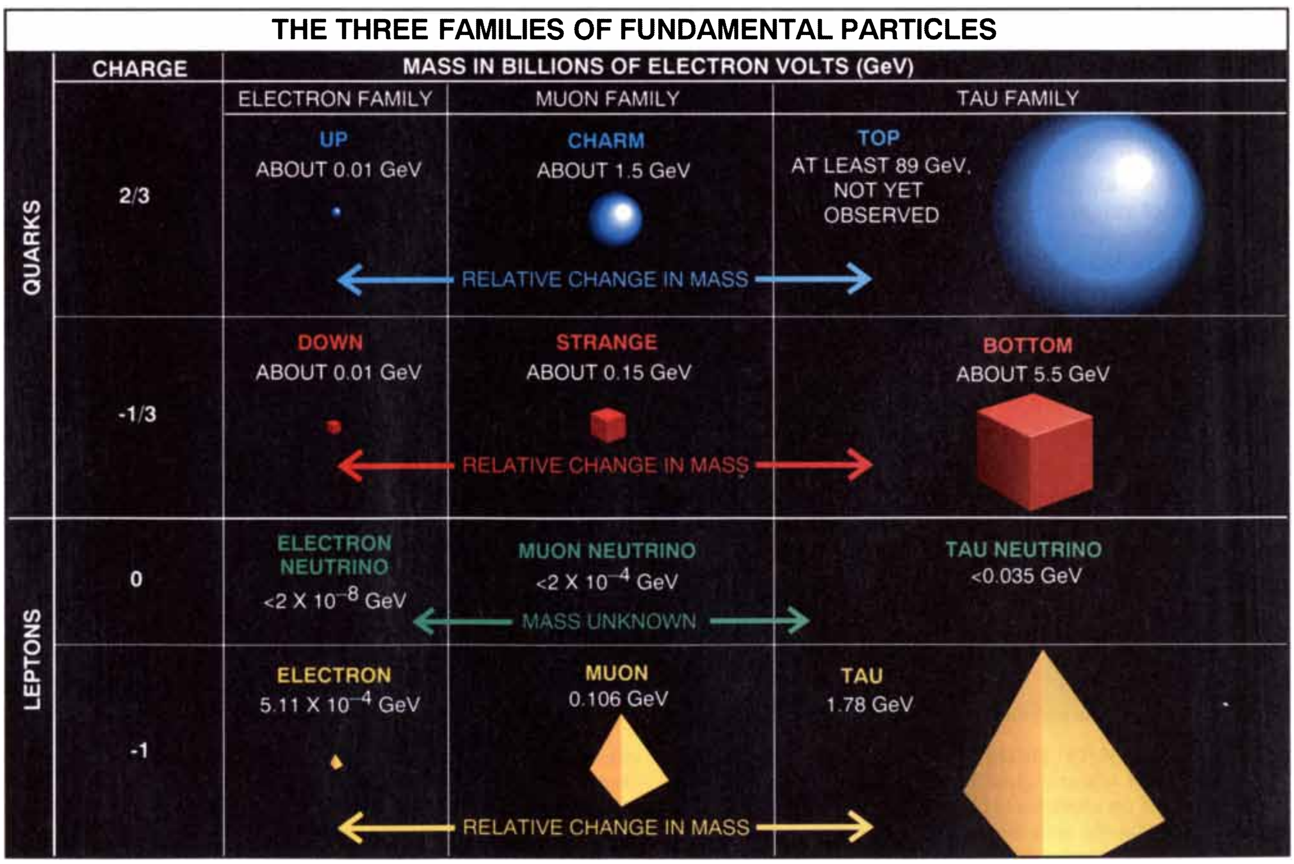
One of the main justifications for building the SLC was that it would serve as a prototype for this new kind of collider. Indeed, the SLC has shown that useful numbers of collisions are obtainable in linear colliders, and it has thus encouraged developmental research in this direction, both at SLAC and at CERN. The present Z production rates at the SLC are, however, still more than 100 times smaller than those at the LEP.

Large teams of physicists analyze the collision products in big detectors. The SLC's detector is called Mark II, and the LEP's four detectors are called Aleph, Opal, Delphi and L3 [*see illustration on page 28*]. The SLAC team numbers about 150 physicists; each of the CERN teams numbers about 400 people, drawn from research institutes and universities of two dozen countries.

The function of a detector is to measure the energies and directions of as many as possible of the particles constituting a collision event and to identify their nature, particularly that of the charged leptons. Detectors are made in onionlike layers, with tracking devices on the inside and calorimeters on the outside. Tracking devices measure the angles and momenta of charged particles. The trajectories are located by means of the ionization trails the collision products leave behind in a suitable gas. Other media, such as semiconductor detectors and light-emitting plastic fibers, are also used.

The tracking devices are generally placed in strong magnetic fields that bend the particles' trajectories inversely with respect to their momenta. Measurement of the curves yields the momenta, which in turn provide close estimates of the energy. (At the energies encountered in these experiments, the energy and the momentum of a particle differ very little.)

Calorimeters measure the energies of both neutral and charged particles by dissipating these energies in successive secondary interactions in some dense medium. This energy is then sampled in a suitable way and localized as precisely as the granularity of the calorimeter allows. Calorimeters perform their function in a number of ways. The



most common method uses sandwiches of thin sheets of dense matter, such as lead, uranium or iron, which are separated by layers of track-sensitive material.

Particles leave their mark in such materials by knocking electrons from their atoms. Argon, either in liquid form or as a gas combined with organic gases, is the usual medium. Plastic scintillators work differently: when a reaction particle traverses them, it produces a flash of light whose intensity is then measured. The calorimeter usually has two layers, an inner one optimized for the measurement of electrons and photons and an outer one optimized for hadrons.

To gather all the reaction products, the ideal detector would cover the entire solid angle surrounding the interaction point. Such detectors were pioneered in the 1970s at SLAC. In the LEP's Aleph detector the tracking of the products from the annihilation of a positron and an electron proceeds in steps.

A silicon-strip device adjoining the reaction site fixes the forward end point of each trajectory to within ten-millionths of a meter (about half the breadth of a human hair). Eight layers of detection wires then track the trajectory through an inner chamber 60 centimeters in diameter. Finally, a so-called time-projection chamber, 3.6 meters in diameter, uses a strong electric field to collect electrons knocked from gas molecules by the traversing particles. The field causes the electrons to drift to the cylindrical chambers' two ends, where they are amplified and detected on 50,000 small pads. Each electron's point of origin is inferred from the place it occupies on the pads and the time it takes to get there.

The next step outward brings the reaction products to the electron-photon calorimeter. The products traverse the superconducting coil, which creates a 15,000-gauss magnetic field at the axis of the device, and then enter the hadron calorimeter. This device, a series of iron plates separated by gas counters, also returns the magnetic flux, just as an iron core does in a conventional electromagnet. Aleph weighs 4,000 tons and cost about $60 million to build. Half a million channels of information must be read for each event, and the computer support necessary for the acquisition and later evaluation of the data is considerable [*see illustration on page 72A*].

The data gathered in the first few months of operation of the two colliders have provided the best support yet adduced for the predictions of the electroweak theory. More important, they have delineated the curve describing the *Z* width with great precision.

The overwhelming majority of observed electron-positron annihilations give rise to four sets of products: 88 percent produce a quark and an antiquark; the remaining 12 percent are divided equally among the production of a tau lepton and antitau lepton, muon and antimuon, and electron and positron. (The last case simply reverses the initial annihilation.)

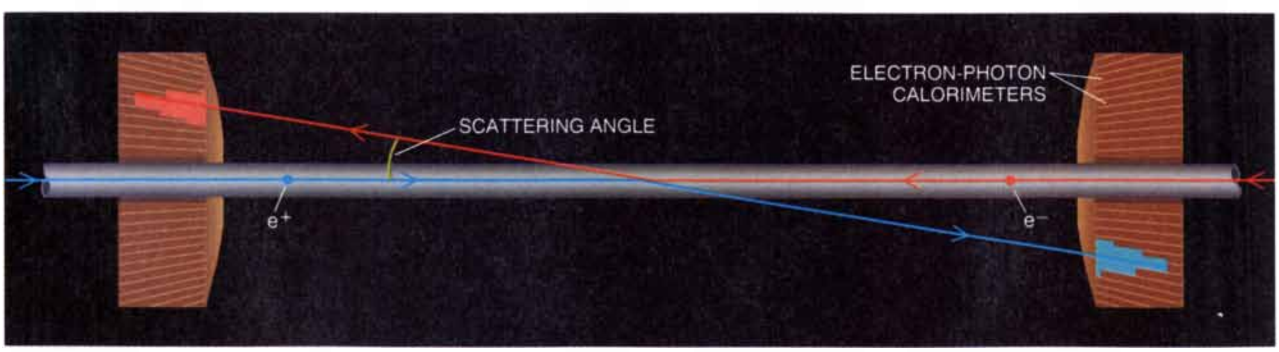
In the decays into electrons and muons, two tracks are seen back to back, with momenta (and energies) corresponding to half of the combined beam energy. The two products are easily distinguished by their distinct behavior in the calorimeters. The decays to tau leptons are more complex because they subsist for a mere instant—during which they travel about a millimeter—before decaying into tertiary particles that alone can be observed. A tau lepton leaves either closely packed tracks or just one track; in both cases, the signature is mirrored by that of another tau lepton moving in the opposite direction (thus conserving momentum).

The quarks that account for most reactions cannot be seen in their free, or "naked," state, because at birth they undergo a process called hadronization. Each quark "clothes" itself in a jet of hadrons, numbering 15 on average, two thirds of which are charged. This, the most complex of the four main decay events, usually manifests itself as back-to-back jets, each containing many tracks [*see bottom left of illustration on page 71*]. The results described here are based on the analysis of about 80,000 *Z* decays into quarks—the combined result of the four LEP teams and the one SLAC team.

The *Z* production curve is determined in an energy scan. Production probability is measured at a number of energies: at the peak energy, as well as above and below it. A precise knowledge of the beam energy is of great importance here. It was obtained at the two colliders very differently, in both cases with a good deal of ingenuity and with a precision of three parts in 10,000.

As was pointed out earlier, the total width of the *Z* resonance can be determined from either the height at the peak energy or the width of the resonance curve. The height has the smaller statistical error but requires knowledge not only of the rate at which events occur but also of the rate at which particles from the two beams cross. The latter rate is called the luminosity of the collider.

In the simple case of two perfectly aligned beams of identical shape and size, the luminosity equals the product of the number of electrons and the number of positrons in each crossing bunch, multiplied by the number of bunches crossing each second, divid-



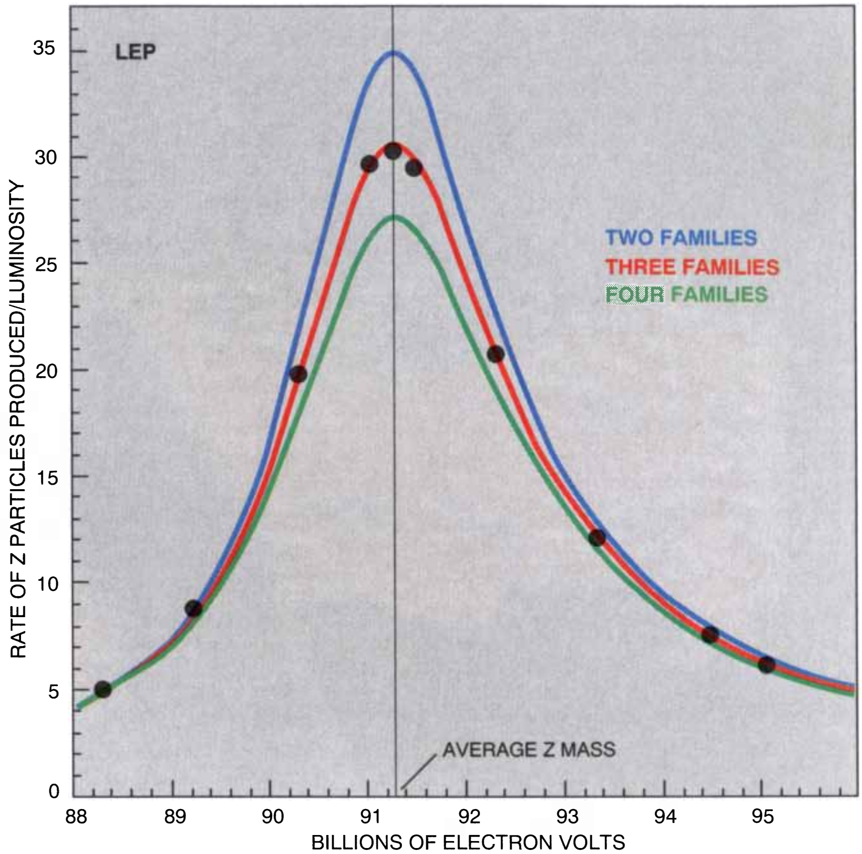
ALEPH'S LUMINOSITY DETECTOR registers a small-angle scattering event when a positron (e^+) enters from the left and glances off an electron (e^-) entering from the right. The particles then hurtle into fine-grained calorimeters that fix their angles and measure their energies. The rate of these events measures the LEP's collision frequency, or luminosity. One must know the luminosity to determine how changes in beam energy affect the probability of producing *Z* bosons. This probability function, in turn, predicts the number of neutrino varieties, hence the number of families of matter.

ed by the cross-sectional area of the beams. In practice, luminosity is determined only by observing the rate of the one process that is known with precision: the scattering of electrons and positrons that glance off one another at very small angles without combining or otherwise changing state. To record such so-called elastic collisions, two special detectors are placed in small angular regions just off the axis of the beam pipe. One of the detectors is in front of the collision area; the other is behind it. In the case of Aleph, these detectors are electron-photon calorimeters of high granularity [*see illustration on opposite page*].

The elastically scattered electrons and positrons are identified by the characteristic pattern in which they deposit energy in the detectors and by the way they strike the two detectors back to back, producing a perfectly aligned path. The essence here is to understand precisely the way in which particles are registered, especially in those parts of the detectors that correspond to exceedingly small scattering angles. This is important because the detection rate is extremely sensitive to changes in the angle.

When the resulting data are fitted to the theoretical resonance shape, three parameters are considered: the height at the peak, the total width and the *Z* mass. The data, in fact, agree well with the shape of the theoretically expected distribution. The next step, then, is to determine the number of neutrino families from two independent parameters—the width and the peak height.

The combined results of the five teams produced an average estimate of 3.09 neutrino varieties, with an experimental uncertainty of 0.09. This number closely approaches an integer, as it should, and matches the number of neutrino varieties that are already known. A fourth neutrino could exist without contradicting these findings only if its mass exceeded 40 billion eV—a most unlikely possibility, given the immeasurably small masses of the three known neutrinos.



RESONANCE CURVES predicted for the *Z* particle vary according to the number of families of matter. Thousands of *Z* decays into quarks, observed at CERN, appear as points. The measurements agree with the expectation for three families of matter.

The *Z* result fits the cosmological evidence gathered by those who study matter on galactic and supergalactic scales. Astronomers have measured the ratio of hydrogen to helium and other light elements in the universe. Cosmologists and astrophysicists have tried to infer the processes by which these relative abundances came about [see "Particle Accelerators Test Cosmological Theory," by David N. Schramm and Gary Steigman; SCIENTIFIC AMERICAN, June 1988].

Shortly after the big bang, the cataclysmic explosion that created the universe and began its expansion, matter was so hot that a neutron was as likely to decay into a proton-electron pair as the latter was to combine to form a neutron. Consequently, as many neutrons as protons existed. But as the universe expanded and cooled, the slightly heavier neutrons changed into protons more readily than protons changed into neutrons. The neutron-proton ratio therefore fell steadily.

When the expansion brought the temperature of the universe below one billion kelvins, protons and neutrons were for the first time able to fuse, thereby forming some of the lighter elements, mainly helium. The resulting abundances depend critically on the ratio of neutrons to protons at the time light elements were forming. This ratio, in turn, depends on the rate at which the universe expanded and cooled. At this stage, each light neutrino family—that is, any whose constituents have a mass smaller than about a million eV—contributes appreciably to the energy density and cooling rate. The measured abundances of light elements are consistent with cosmological models that assume the existence of three light neutrino families but tend to disfavor those that assume four or more.

Many questions remain unanswered. Why are there just three families of particles? What law determines the masses of their members, decreeing that they shall span 10 powers of 10? These problems lie at the center of particle physics today. They have been brought one step closer to solution by the numbering of the families of matter.

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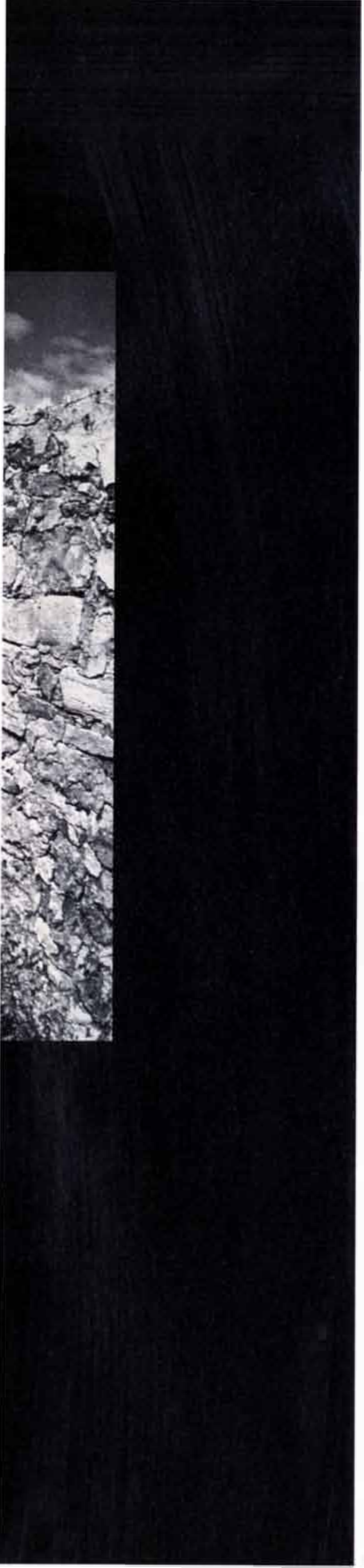

"Vision is the art of seeing things invisible."

Jonathan Swift

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