

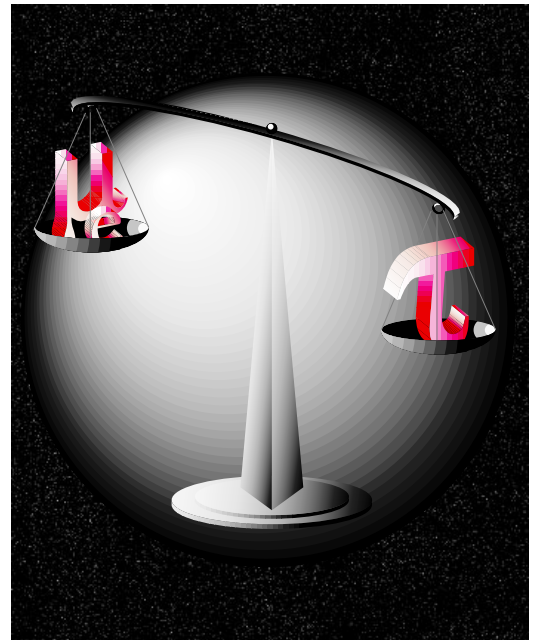
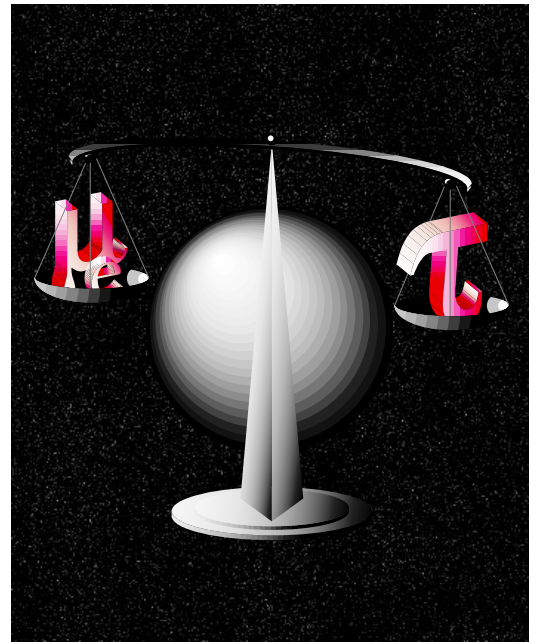
# LEPTON UNIVERSALITY

by J. RITCHIE PATTERSON

*“You know, it would be sufficient  
to really understand the electron.”*

*—Albert Einstein*

**A**LL OF US ARE FAMILIAR with the electron as the small companion of the atomic nucleus. It is the atomic nucleus that gives ordinary matter its weight, but the electron is responsible for the space that matter fills, for while it is small, the electron rules vast territories. The electron was first discovered thanks to the electric charge that it carries, and we rediscover the electron whenever we happen to get an electrical shock.



$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}$$

$$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$$

$$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

Indeed, the root “electro-” comes from the Greek word meaning amber, so named because amber tends to accumulate electric charge when rubbed, just as we do when we shuffle across a wool rug.

While the electron is unique in the role that it plays in ordinary matter, it is actually part of a trio. The electron’s partners, called the muon and the tau, have the same electric charge and seem to share its other properties as well. All its properties, that is, except one: their masses are very different. The muon is heavier than the electron by a factor of about 200, while the tau is heavier by the whopping factor of 3500. These three particles are three of twelve known fundamental particles of nature.

The muon, which we write as  $\mu$ , was discovered in 1947 in cosmic rays. At the time of its discovery, physicists had untangled quantum mechanics and understood atomic structure and the nucleus. The puzzles of nature had apparently been solved, and many physicists were ready to declare victory and retire. The appearance of a new particle came as a surprise, and not an entirely welcome one. As I. I. Rabi said at the time, “Who ordered this?”

The tau ( $\tau$ ) is a much more recent discovery. It was found in 1975 by a group led by Martin Perl at the SPEAR particle accelerator at SLAC. This group observed that the collision of an electron with an anti-electron (or “positron”) sometimes produced particles in a configuration inconsistent with all known processes. Instead, it was exactly what one would expect if new particles were being produced that were similar to electrons, but much heavier.

As far as we know, the electron, muon and tau are fundamental particles, and unlike molecules or atoms, they cannot be broken down into smaller components. This is not the first time that we have thought we have found the fundamental building blocks of nature, and in the past we have often been wrong. Ordinary matter turned out to be made of molecules, molecules of atoms, atoms of nuclei and electrons, nuclei of protons and neutrons, and, most recently, protons and neutrons of quarks. But the electron, muon and tau appear to be indivisible: we see no sign of constituents and they are minuscule in size. In fact, surprising as it may seem, they may be pointlike, with no spatial extent at all.

How do we measure the size of the electron? Just as the electron has electric charge, it also has an intrinsic angular momentum that is constant in time. We call this angular momentum “spin” and measure it in units of Planck’s constant  $\hbar$ , which, like the speed of light, is a fundamental constant of nature. The spin of the electron (and the muon and tau) is  $\hbar/2$ . Like all circulating electric charges, the electron’s spin generates a magnetic field similar to the one around the earth, the strength of which depends on the spatial distribution of its charge. Calculations of this magnetic field have been carried out for the electron using the theory of quantum electrodynamics (QED) with the assumption that the electron is pointlike. The results agree with the experimental value within one part in one billion. This is the most precise test of theory and experiment in physics, and the agreement is a triumph for QED.

It tells us that the electron is small indeed: the agreement would be spoiled if the radius of the electron were greater than about  $10^{-14}$  centimeters.

Colliders provide an even more powerful microscope into the electron’s structure. By studying the deflections of electrons and anti-electrons when they collide with one another, experimenters in Japan and Europe have probed the electron on a scale as small as  $10^{-17}$  cm, but they see no sign of substructure. Equally precise studies of the muon also yield null results. We know much less about the tau, but so far, it too appears to be free of smaller constituents.

**T**HE ELECTRON, MUON and tau are not alone. Each has a partner called a neutrino, written as  $\nu_e$ ,  $\nu_\mu$  and  $\nu_\tau$  respectively. The neutrinos are massless or nearly so, are electrically neutral, and are insensitive to the strong force that binds atomic nuclei. As a result they are rarely detected. When they were first proposed by Wolfgang Pauli in order to explain the apparent loss of energy and momentum in radioactive decays, he apologized, “I have done a terrible thing, I have postulated a particle that cannot be detected.”

Neutrinos may be hard to detect, but they are not rare. In fact, they are produced abundantly in the sun, and more than  $10^{13}$  pass through your body each second, and then continue through the earth and out the other side. Of these, only one per year interacts in your body, leaving a brief ripple in its wake. Like the electron, muon and tau, the neutrinos



are believed to be carbon copies of one another. All have the same spin and the same weak charge, and like the electron, muon and tau, they are believed to be fundamental particles.

What links the  $e$  and  $\nu_e$  as partners? In radioactive decays, we see that the  $e$  is always accompanied by a  $\nu_e$ , but never, say, by a  $\nu_\mu$  or a  $\nu_\tau$ . That the neutrino species are distinct was first demonstrated in 1962 by Leon Lederman, Mel Schwartz, Jack Steinberger and their collaborators in an experiment which earned them the Nobel prize.

**T**HESE SIX PARTICLES, the electron, muon and tau plus their three neutrinos are known as “leptons,” a name derived from the Greek word  $\lambda\epsilon\pi\tau\sigma$  meaning small or light. (Had early particle physicists known about the weighty  $\tau$ , they might have chosen a different name!) High energy physicists like to arrange the leptons in a special way (see figure on right), and refer to each lepton and its neutrino as a generation. The generations are ordered by the masses of the charged leptons.

In addition to the leptons, there is another set of particles called quarks. Quarks are similar to leptons, but unlike leptons, can interact via the strong force. We know of six kinds (or “flavors”) of quark: “down,” “up,” “strange,” “charm,” “bottom,” and “top.” All of these are produced prolifically at accelerators except the “top” quark, for which the first direct evidence was reported last year by particle physicists at the Fermi National Accelerator Laboratory located outside Chicago. Quarks are the building blocks of protons and neutrons (a proton is made of two

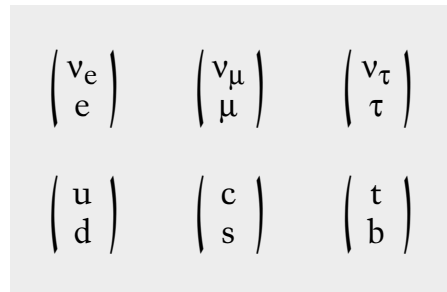
“up” quarks and one “down” quark while a neutron is made of one “up” quark and two “down” quarks). All other particles that we have observed (other than the leptons), such as the  $\pi$  meson, are bound states of the quarks.

Like the leptons, the six quarks seem to come in pairs, and their masses range from very small in the first generation to very large in the third generation. In fact, the top quark weighs about as much as a gold nucleus. Why there should be three generations, and the relationship between the lepton and quark generations, are mysteries.

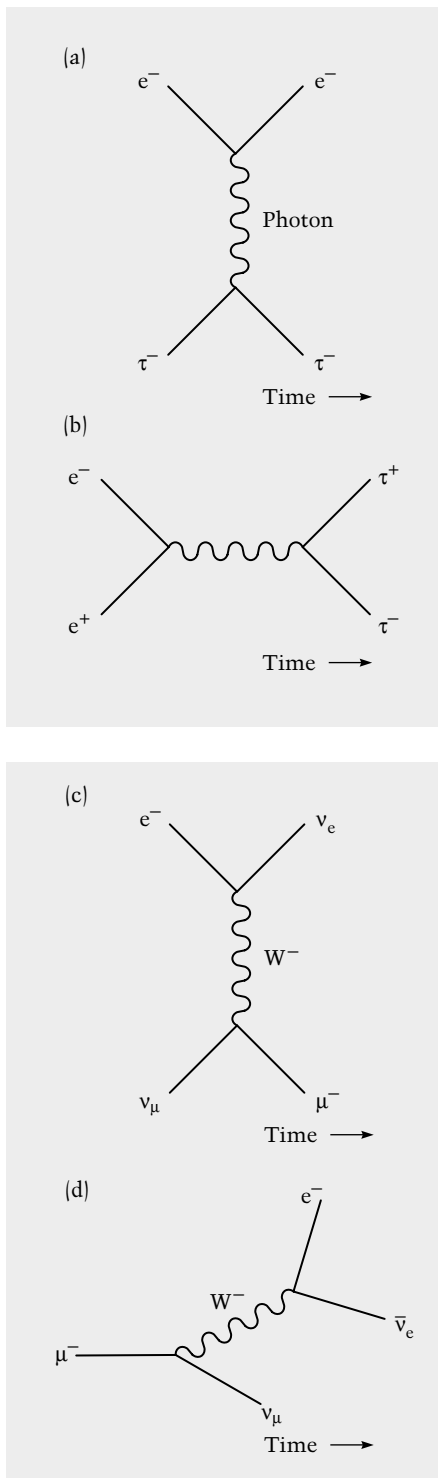
Could there be a fourth generation of quarks or leptons waiting to be discovered? Current evidence suggests not. Data from the LEP accelerator at CERN in Geneva, Switzerland have shown that there are only three species of light (or massless) neutrinos: these are the  $\nu_e$ ,  $\nu_\mu$ , and  $\nu_\tau$ . Thus, if an additional generation exists, its neutrino must be very massive—a marked departure from the generations that we now know.

**F**ORCES THAT CONTROL the interactions between particles are as essential to nature as the particles themselves. We know of four forces: gravity; electromagnetism; the “strong” force, which binds together quarks into protons, neutrons,  $\pi$  mesons or other, less common, particles; and the “weak” force, which is responsible for the decay of radioactive nuclei and for much of the activity in the sun.

All of the forces operate in about the same way. Associated with each one is a charge: electric charge for electromagnetism, mass for gravity,



*The known fundamental particles of nature. The upper six particles are the leptons and the lower six are the quarks. Both the leptons and the quarks are arranged into three generations of two particles each (shown in brackets).*



A particle physicist's view of electromagnetic interactions. In the upper figure (a) two charged particles, each represented by a solid line, scatter. A photon carrying energy and momentum is emitted by one and absorbed by the other. The lower figure (b) shows the less familiar annihilation of an electron and anti-electron. Their energy goes into the photon which then materializes into two new particles—in this case a tau and anti-tau.

and something called "color" for the strong force (this "color" has nothing to do with the usual meaning of the word). Similarly, there is a "weak charge" associated with the weak force. Electrons, muons, and taus carry this charge as do the neutrinos and quarks.

When Newton developed the concept of force, he viewed it as "action at a distance." We now know that special particles travel between the interacting objects, deflecting them with the momentum and energy which they carry. In the case of gravity, this special particle is the graviton, while for electromagnetic interactions it is the photon.

It is handy to diagram these processes as shown in the adjacent figures. In these diagrams, each particle is represented by a line, and time increases from the left hand side of the diagram to the right. In diagram (a), the electrical repulsion of two charged particles, the particles are well-separated at the left-hand side of the diagram, they approach each other, and exchange a photon, which is represented by the wiggly line, and recoil. These diagrams are convenient for high energy physicists because they can be translated into mathematical formulae for the probability that the scattering will occur: using a method first introduced by Richard Feynman, one simply writes down a mathematical factor for each line and intersection point.

The repulsion or attraction of two charged particles is the most familiar electromagnetic interaction, but it is not the only possibility. As shown in diagram (b), a particle and its anti-particle can meet and annihilate one another to produce a

photon which then materializes as a new particle and anti-particle pair. This is how particles such as taus were produced at the SPEAR and PEP storage rings at SLAC and are currently produced at the CESR electron-anti-electron collider at Cornell University. Note that this diagram is identical to figure (a) rotated by 90 degrees except that some particles have been changed from particle into anti-particle and vice versa. As the similarity of the diagrams suggests, the same physics is responsible for both processes.

Weak interactions work in the same fashion as the electromagnetic and gravitational interactions. When two particles carrying the weak charge approach one another, they can exchange a particle, in this case either a "W-boson" or "Z-boson." The W-boson was first observed directly in 1983 by two groups at CERN, one led by Carlo Rubbia, and is now produced routinely at the proton collider at Fermilab, and the Z-boson is produced and studied in detail at the LEP collider at CERN and at the SLC at SLAC.

Just as the photon materializes into a pair of particles, so does the W. For the W, this can be either a pair of leptons or a pair of quarks. Whenever the W decays into leptons, it always chooses two leptons from the same generation: an  $e$  and  $\nu_e$ , a  $\mu$  and  $\nu_\mu$ , or a  $\tau$  and  $\nu_\tau$ . In fact, experiments have searched for decays in which the W (or some unexpected exotic particle) produces leptons from two different generations, and none have been observed, even though some of these experiments, such as one known as SINDRUM at the Paul Scherrer Institute in Switzerland and

A particle physicist's view of the weak interactions. In the upper figure (c) an electron and muon neutrino exchange a W-boson, and a muon and electron neutrino emerge. In the lower figure (d) a muon decays by emitting a W-boson and neutrino, and the W then materializes as an electron and electron anti-neutrino. This process is very similar to radioactive decay as well as much of the activity in the sun.

another at the Los Alamos National Lab in New Mexico known as MEGA, have searched among nearly 1 trillion decays. Interestingly, when the W decays into quarks, it disregards the ban on cross-generational mixing. This cross-generational quark mixing has some fascinating consequences, some of which motivate the construction of the new accelerators known as B-factories.

We can now explain why we find electrons rather than muons inside atoms. The weak interaction allows a muon to decay into an electron plus two neutrinos, as shown in diagram (d), in a process that is very similar to the radioactive decay of an atomic nucleus. Muons typically survive  $2 \times 10^{-6}$  seconds before decaying in this way. The reverse process, the decay of the electron into a muon plus neutrinos, is forbidden by energy conservation because the muon is heavier than the electron.

The mass of the lightest lepton has a major impact on our day to day lives. What would happen if the electron were as heavy as a muon? For starters, atoms would be much more compact because the large centrifugal force of these heavy electrons could be overcome only if they hugged the atomic nucleus. As a result, an apple would weigh about what it does now, but it would be the size of a grain of sand. Similarly, a typical person, if she or he could survive at all, which is doubtful given the consequences of heavy electrons for chemistry, would stand only one third of an inch tall.

Like the muon, the tau can decay into an electron plus neutrinos, but its large mass gives it a multitude of other possibilities. For example, it

## MODERN PARTICLE DETECTORS

**A** TYPICAL MODERN particle detector is really a collection of many devices each with its own capabilities. These devices are layered around one another like the peels of an onion, all centered on the point where the two accelerated particle beams collide.

In most detectors, the innermost layers display the trajectories of charged particles. By placing these devices in a large magnetic field, we learn not only the particle's direction of travel, but also its momentum, which is inversely proportional to its curvature in the magnetic field. Other devices measure the particle's velocity, which combined with the momentum measurement reveal its mass and therefore its identity. Yet other devices detect photons and other electrically neutral particles.

Each of these devices produces electrical signals which are

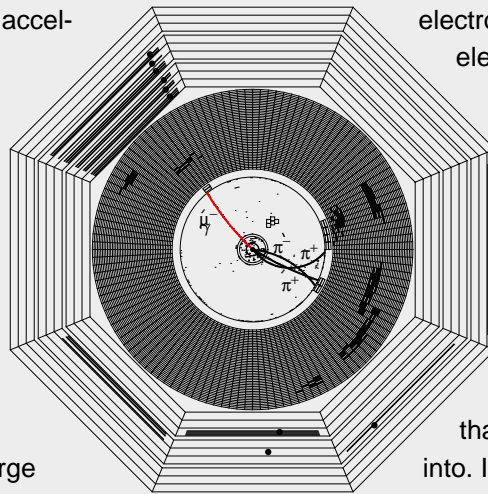
digitized and recorded for later analysis whenever something interesting happens in the detector.

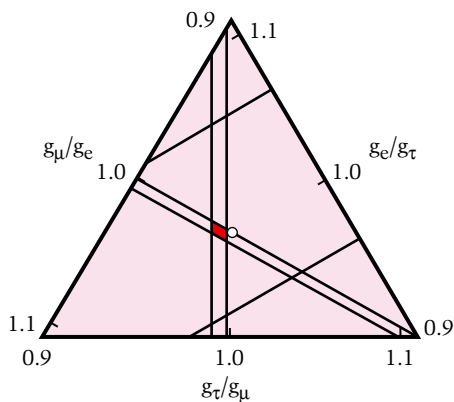
The figure shows the signals in the CLEO detector at Cornell University when an

electron and anti-electron annihilate to produce a pair of taus. The taus decay before reaching the detector, so we see only the particles that they decay into. In this event, one tau traveling up

and to the left decays into a muon and two neutrinos, while the other, traveling down and to the right, decays into three pions plus a neutrino. We recognize the muon by the signal that it leaves in the outermost layers of the detector—it is the only particle that penetrates that far. The neutrinos escape undetected.

Events like this one can be used to measure the tau lifetime.





This “Universality Triangle” helps physicists assess the weak charges of the leptons. The two vertical lines indicate the band of values of  $g_\tau/g_\mu$  compatible with recent measurements. The bands of allowed values of the other two ratios of weak charges are indicated by lines perpendicular to the other two sides of the triangle. If  $g_e$ ,  $g_\mu$ , and  $g_\tau$  are identical, then the bands will overlap at the center of the triangle. On the other hand, if one charge differs from the other two, then the overlap region (which is shaded) will march toward one corner of the triangle.

may decay into a muon plus neutrinos in an analogous process or even into quark pairs plus a neutrino.

Because it has so many decay options, the tau is very shortlived. The average lifetime of the tau is 0.3 trillionths of a second. This has been measured at accelerators where taus are produced. At the SLC collider at SLAC and the LEP collider in Europe, taus travel about 2 cm in their lifetime, which is easily measurable with modern particle detectors.

What evidence do we have that the electron, muon and tau are identical apart from their masses? This is a topic of current research. Currently, physicists test whether the weak charges of the muon and tau are identical by comparing their decay rates into an electron plus neutrinos. Calculations of the Feynman diagrams indicate that the ratio of the tau to muon decay rates should be proportional to  $(m_\tau/m_\mu)^5 (g_\tau/g_\mu)^2$ , where  $g_\mu$  and  $g_\tau$  are the weak charges of the  $\tau$  and  $\mu$  and  $m_\tau$  and  $m_\mu$  are their masses. Recent measurements of the tau mass done at BEPC in Beijing, China, and decay rate done most precisely at LEP (the muon has been around for years and its mass and decay rate are very precisely known) show that the ratio of weak charges is  $g_\tau/g_\mu = 0.994 \pm 0.004$ , where  $\pm 0.004$  indicates the experimental uncertainty. We see that the ratio of the muon and tau weak charges is nearly unity, and that if they differ, it is only by a tiny fraction. In fact, the ratio of weak charges differs by an amount slightly larger than the experimental error. Future, more precise, experiments

will reveal whether this discrepancy is significant.

The ratios of weak charges  $g_\mu/g_e$  and  $g_e/g_\tau$  have also been measured at TRIUMF in Vancouver and at Fermilab and CERN respectively, and the results are summarized in the adjacent figure. If the weak charge of one of the leptons were larger than the others, the overlap band shown in the figure would move from the center of the triangle toward one of the corners. In fact, as far as we can tell now, their weak charges are identical. Even a minute difference, however, would signal a profound discovery, so future research will attempt to determine these charges even more precisely.

It may seem surprising that particles whose properties and interactions seem to be identical should have such different behavior: the electron, a principal player in everyday matter; the muon, found primarily in cosmic rays; and the tau, confined to particle accelerators. But as far as we know, the tau and the muon are simply heavy replicas of the electron—only their vastly different masses are responsible for the very different roles that they play in our universe.

Many questions remain. Why are there three generations? Where do they get their masses, and why do they differ so drastically from one another? Why do the weak interactions always produce leptons within a single generation? Is it a coincidence that there are also three generations of quarks? Someday we may know the answers to these questions.

