produced together with electrons in nuclear beta decay. After Schwartz’s pivotal experiment, particle physicists began calling the former “muon neutrinos” (or $\nu_\mu$) to distinguish these particles from the latter, known as “electron neutrinos” (or $\nu_e$). Whenever a positive muon decays, for example, it yields a positron, an electron neutrino and a muon antineutrino ($\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$). By 1962 physicists recognized four distinct “leptons,” or light particles: the electron, the muon, and their two respective neutrinos (plus antiparticles).

Theoretical and experimental advances over the ensuing decade resulted in a revolutionary new picture of the subatomic realm that came to be known as the Standard Model of particle physics. In this theory, leptons and other particles called “quarks” are regarded as elementary, point-like entities. The electromagnetic and weak interactions, previously thought of as distinct forces with vastly differing strengths, are now considered to be just two different aspects of one and the same “electroweak” interaction. The extreme feebleness of the weak interaction arises because it occurs via the exchange of ponderous spin-1 particles known as “gauge bosons,” which are difficult to conjure up out of sheer nothingness. In beta decay, for example, a neutron coughs up a massive, negatively charged W boson and transforms into a proton ($n \rightarrow p + W^-$); the $W^-$ immediately converts into an electron plus its antineutrino ($W^- \rightarrow e^- + \bar{\nu}_e$). Only the left-handed electrons and neutrinos (and their right-handed antiparticles) participate in these weak interactions, thereby yielding their characteristic parity-violating property.

An inescapable requirement of this unification of the electromagnetic and weak interactions is the existence of “neutral currents” that occur due to exchange of another massive, but neutral, boson $Z$. Instead of converting into a muon when it interacts with a nucleus via the exchange of a $W$ boson, for example, a muon neutrino can instead glance away unaltered, remaining a muon neutrino.

After years of searching, neutral currents were discovered in 1973 by an international collaboration of physicists working at the European Center for Nuclear Research (CERN) on the Gargamelle bubble chamber. Filled with liquid freon, it was exposed to beams of muon neutrinos and antineutrinos from CERN’s proton synchrotron. The initial evidence came from a few rare events in which these spookinos rebounded elastically from atomic electrons (for example, $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$), and imparted energy to them. These
electrons left wispy tracks in the chamber, whereas the neutrinos or antineutrinos crept away undetected. Subsequent confirmation came from Gargamelle and two experiments at Fermilab in which muon neutrinos scattered inelastically from nuclei. By the mid-1970s, it was clear that neutrinos (and, in fact, all the other leptons and quarks) were capable of a new kind of weak interaction in which they maintained their identity instead of transforming into a partner lepton (or quark). The discovery of these neutral currents, together with conclusive evidence for a fourth, or charm, quark c to accompany the initial trio—up u, down d, and strange s—provided strong support for the Standard Model. Quarks and leptons come in pairs: u and d, e and νe, c and s, µ and νµ. What’s more, quark and lepton pairs can be grouped into families of four, often called “generations.” Two such families were recognized by 1976: the first includes the up and down quarks plus the electron and electron neutrino, while the second contains the charm and strange quarks plus the muon and muon neutrino. Particle physicists could now discern a highly satisfying symmetry among the elementary entities in their new ontology.

Three years earlier, two Japanese theorists had suggested that a third family of quarks and leptons might exist. Makoto Kobayashi and Toshihide Maskawa were seeking a way to incorporate the mysterious phenomenon of CP violation within the emerging structure of what was soon recognized as the Standard Model. Discovered in 1964 by James Cronin, Valentine Fitch, and their colleagues, this phenomenon indicated that—at least in certain decays of kaons—Nature is asymmetric under the combined operations of charge conjugation (C) and parity inversion (P). They observed that kaons behave differently, that is, if one replaces particles by antiparticles and views their interactions in a mirror. Kobayashi and Maskawa could not obtain this CP violation using only the two known families of quarks and leptons. But if they added a third family to the mix, including two more quarks plus another charged lepton and its neutrino, they discovered that it arose naturally.

At about the same time, Martin Perl and his colleagues were beginning their search for another heavy, charged lepton using the SLAC-LBL detector at the new electron-positron collider SPEAR. If such a heavy lepton...
difficulties of making a sufficiently intense beam of tau neutrinos and detecting them unambiguously. Meanwhile, the two quarks expected in the third family—the bottom $b$ and top $t$ quarks—were isolated at Cornell and Fermilab, leaving only the elusive tau neutrino remaining to be discovered. So dominant had the Standard Model become that few particle physicists seriously questioned its existence.

Cosmological arguments about nucleosynthesis of light elements during the first few minutes of the Big Bang required that a third neutrino—and perhaps even a fourth—ought to exist. The abundance of primordial helium-4 synthesized during this process is determined by the expansion rate of the Universe at that time, which is sensitively related to the number of different kinds of light neutrinos. As measurements became more accurate during the 1980s, primordial helium-4 was observed to contribute about a quarter of the visible mass in the Universe, suggesting a third (and a remotely possible fourth) kind of neutrino.

By 1974 Perl’s group began to find such “anomalous $\mu$ events” in the data samples being collected on the SLAC-LBL detector, and by 1975 they had dozens (see diagram on the left). But convincing their colleagues that these events were conclusive evidence for a heavy lepton took longer. In 1977, confirmation of the SLAC results began to come in from the DORIS electron-positron collider in Hamburg. Further experiments on SPEAR and DORIS showed the mass of this tau lepton $\tau$ to be around 1.78 GeV and identified its decay into a pion and tau neutrino ($\tau^- \rightarrow \pi^- + \nu_{\tau}$). By the following summer, there was little doubt among particle physicists regarding the existence of the tau lepton.

Still, it took physicists over two more decades to achieve the direct detection of a free tau neutrino, well separated from its point of production. The problem occurred due to the difficulties of making a sufficiently intense beam of tau neutrinos and detecting them unambiguously. Meanwhile, the two quarks expected in the third family—the bottom $b$ and top $t$ quarks—were isolated at Cornell and Fermilab, leaving only the elusive tau neutrino remaining to be discovered. So dominant had the Standard Model become that few particle physicists seriously questioned its existence.

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The issue was settled in 1989 by terrestrial experiments at new electron-positron colliders—the SLC at SLAC and LEP at CERN—that were capable of producing hordes of $Z$ bosons. Within the structure of the Standard Model, additional kinds of neutrinos give this particle additional pathways to decay, thereby shortening its lifetime. By making precision measurements of the $Z$ resonance peak, physicists at the two facilities concluded that there are three, and only three, kinds of “conventional” light, weakly interacting neutrinos. Confirming the cosmological predictions, these experiments put a firm lid on the complexity of the Universe. Its table of fundamental entities could have only three families of quarks and leptons (see illustration below).
Direct experimental evidence for the tau neutrino came finally in 2000, seventy years after Pauli conceived his novel idea. By examining millions of particle tracks left on special three-dimensional photographic film, physicists working on the DONUT experiment at Fermilab found four events that could only be interpreted as a tau neutrino colliding with a nucleus and producing a tau lepton. (For further details, see the article by Paul Nienaber, this issue.) The third and final neutrino had finally left subtle, indirect footprints that confirmed its long-anticipated existence.

The idea of the neutrino has therefore evolved substantially since its conception in the early 1930s. Pauli’s tenuous hypothesis was just the starting point for a lengthy process of theoretical and experimental elaboration that continues today. Where he at first regarded neutrinos as nuclear constituents, Fermi showed how they can instead be created in nuclear transformations. Where Pauli sought a minimal way to preserve the conservation of energy and angular momentum in individual beta decays, physicists have recently established that at least two—and most likely all three—of the neutrinos have a tiny bit of mass. And where he speculated that this mass might well be greater than an electron’s, physicists now think it must be at least a million times smaller.

But despite the great transformations that have occurred in the idea of the neutrino since 1930, Pauli deserves due credit for being the one daring enough to take the great conceptual leap of introducing another fundamental entity into the minimalist ontology of his day. No doubt the enduring success of his bold scheme has encouraged theorists of later decades to repeat this exercise whenever a cherished symmetry or conservation law appears to be violated. In this subtle way, the ghost of Wolfgang Pauli still haunts the way particle physics is practiced today.

For Further Information

Good summaries of the history of neutrinos can be found at:

http://wwwlapp.in2p3.fr/ neutinos/aneut.html

http://www.ps.uci.edu/~superk/ neutrino.html

On Wolfgang Pauli, see:

http://www.physicstoday.com/pt/ vol-54/iss-2/p43.html

http://www-groups.dcs. st-andrews.ac.uk/~history/ Mathematicians/Pauli.html
THE COMMUTE is only four kilometers, but it can take an hour each way. The problem is neither traffic nor mass-transit delays, but the fact that the trip takes you 6800 feet below the surface of the Earth. Much of the time is taken up by the required safety rituals: donning the reflective coveralls and hardhat, lacing up the steel-toed work boots, buckling the headlamp battery into the safety belt and placing your name tag on the peg board.

The schedule of a busy mine is driven by the need to move equipment—not people—from level to level. You wait by the mine shaft until the “on-shift boss” decides it is convenient to bring you down and calls for your levels: “Sixty-two to seven-thousand!—going down.” Both miners and physicists then climb into an open steel box (the “cage”), which is suspended by a cable as thick as a man’s leg. The cage comfortably fits twenty people; it usually holds closer to sixty. On a good day, you can place both feet on the floor.

While the drop downward starts slowly, it eventually reaches a top speed of about 2200 feet/minute. Headlamps provide the only light, and you can just make out the rock wall of the shaft as it rushes upward past your face. Occasionally the darkness is broken by a brief glimpse of one of the shallower mining levels blinking by so fast that you barely register an image of a lighted tunnel receding away. By the 4000-foot level, your ears start to feel the additional pressure, and even the most seasoned miners snort and work their jaws trying to adjust.
If they don’t stop to let off miners on one of the shallower levels, the trip down to the 6800-foot level takes less than four minutes. As you step off the cage, a sign long-ago covered in grime declares that this is “The Home of the Sudbury Neutrino Observatory.” To the miners, it is just another level rich with nickel.

The commute is not yet over, however, as there is still over a mile’s worth of hiking left at this level. The dark and the dust and the mud are typical of any of the mine’s other tunnels (called “drifts”), as is the fact that the rock above your head—nearly a mile and a half of it—is kept from collapsing only by a brute-force combination of bolts 30-feet long, steel screening, and concrete. Without that support, the pressures at this depth are so great that the rock would quickly crumble.

A stiff breeze blows at your back, ventilation that keeps the air throughout most of the mine near $70^\circ F$ all year round—much cooler than the natural $100^\circ F$ of the rock. In some pockets where the ventilation doesn’t reach, the air is as hot and humid as a summer day in Philadelphia.

The (quite literal) light at the end of this tunnel shines on two plain-looking blue doorways—one for people and one for railcars. The accumulated dirt and mud on your boots must be washed off before you enter, and once inside, the contrast with the conditions in the drift could not be more striking: bright lights, dust-free air, spotless floors, and white painted walls suddenly make it hard to remember that you’re at the bottom of one of the world’s deepest mines. To go further inside, you need to clean off even more: the boots, hardhat, and coveralls come off, and everyone must shower and change into clean clothes and a hairnet.

Computers, fax machines, coffee makers, telephones—they make it almost impossible to convince yourself that there is a mile and a half of rock above your head! And there is more: a water purification plant, a control room where shift operators monitor and alter the way data are taken, and a darkened, domed area with rack upon rack of flickering data-acquisition electronics. Only the fact that there are no windows—no way to see the Sun from a mile and a half underground—reminds you of where you are. Which is perhaps ironic, given that the principal purpose of the Sudbury Neutrino

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The SNO detector just before completion of the bottom of the acrylic vessel. The acrylic used for this vessel is over 2.5 inches thick and built to hold 1000 tons of heavy water.
Observatory (SNO) is to study sunshine—not the sunshine visible to the human eye, but sunshine made of neutrinos, which travel to the bottom of the mine more easily than sunlight through a pane of glass.

THE SOLAR NEUTRINO PROBLEM

The sunshine that flows through windows—and down to the bottom of mines—is born in a tremendous nuclear reactor that rests at the center of the Sun. Sir Arthur Eddington first suggested that the energy stored in atomic nuclei provides the Sun’s power, pointing out in 1920 that this source was “well-nigh inexhaustible” and “sufficient . . . to maintain [an] output of heat for 15 billion years.” (See John Bahcall’s article in the Winter 2001 Beam Line, Vol. 31, No. 1.) But proving that the Sun is tapping nuclei for energy is not easy—it requires the detection of some specific signature other than the light and heat that we see and feel (most of which is coming directly from the boiling surface of the Sun, not its center). Fortunately for us, the neutrino is a common by-product of nuclear reactions, and therefore observation of solar neutrinos on Earth can prove Eddington’s hypothesis.

It was not until 1967, however, that Brookhaven National Laboratory scientist Ray Davis and his coworkers constructed the first detector to look for neutrinos coming from the Sun. Davis’s experiment was not only expected to be a triumphant confirmation of the theory but also to usher in a new era of solar physics in which neutrinos would be used to probe the details of the solar core. Yet, while Davis did prove that the Sun emits neutrinos, his measurements also produced a surprise: compared to the detailed calculations made by John Bahcall and others, he detected far fewer neutrinos than expected. The five experiments that came after his also saw similar deficits. The mystery of these “missing” neutrinos is known as the solar neutrino problem, the oldest puzzle in experimental particle physics.

Essentially there are three possible ways in which neutrinos from the Sun might seem to be missing. First, the measurements may simply be incorrect: the neutrinos are present, but we have undercounted them. But the different detectors and approaches used by the various solar neutrino experiments make a common error between them very unlikely. Second, the theory of the Sun may be wrong in some way; perhaps the Sun’s interior properties are different from what is expected, and fewer neutrinos are being created. The theory of the Sun correctly predicts other solar characteristics, such as the way in which the Sun’s surface vibrates in response to seismic activity, and it is therefore unlikely that we would grossly miscalculate the number of neutrinos. We are left with a third possibility: that the problem is not due to our measurement of neutrinos or our understanding of the Sun, but to something about the neutrino itself.

Davis’s experiment therefore provided much more than a new way to study the Sun: it raised questions about a part of fundamental particle physics we thought we already understood. Our best theory of
elementary particles, the Standard Model, holds that there are three different types (or flavors) of neutrinos—electron neutrinos (written $\nu_e$), muon neutrinos ($\nu_\mu$), and tau neutrinos ($\nu_\tau$) each closely associated with the corresponding charged particle. The Sun can produce only electron neutrinos, and therefore the six solar-neutrino experiments prior to SNO have searched primarily for this one flavor. But if the Standard Model is wrong, and the three flavors of neutrinos are not completely distinct but can change from one type into another, we may have an explanation for the solar neutrino problem. If the electron neutrinos born in the center of the Sun change into one of the other types on their way to Earth, then the earlier experiments will have recorded fewer neutrinos than expected; the changelings would sail right through the detectors without being noticed.

The changing of neutrinos back and forth from one flavor to another is usually referred to as neutrino oscillations (see Maury Goodman’s article in the Spring 1998 Beam Line, Vol. 28, No. 1). Strong evidence that neutrinos can oscillate from one flavor to another was reported in 1998 by the Super-Kamiokande experiment in Japan, which observed muon neutrinos produced in the Earth’s upper atmosphere by cosmic rays. What Super-Kamiokande observed was that the number of muon neutrinos measured depends on where the muon neutrinos were produced—above the detector, where they needed to travel only 10–100 km before observation, or below it all the way on the other side of the Earth, where they would have to travel...
thousands of kilometers to reach the detector. If muon neutrinos can oscillate into another type of neutrino, they would produce exactly the type of up-down, distance-dependent difference in the number of neutrinos witnessed by Super-Kamiokande (see John Learned’s article in the Winter 1999 Beam Line, Vol. 29, No. 3).

For solar neutrinos, however, the distance from the production point (the Sun) to the detection point (the Earth) does not vary enough to allow the kind of measurements made with Super-Kamiokande’s atmospheric muon neutrinos. Rather than look for distance-dependent effects, the way to prove that the electron neutrinos produced in the Sun are oscillating into muon neutrinos or tau neutrinos is to search directly for evidence of these neutrinos. SNO is designed to do just that: determine whether or not solar neutrinos other than electron neutrinos are arriving from the Sun. If this were true, it would not only solve the long-standing solar neutrino problem, but also provide the most direct evidence yet that neutrinos do indeed oscillate.

THE SUDBURY NEUTRINO OBSERVATORY

Like an invisible man on the beach who can be “seen” only by tracking his footprints, neutrinos can be observed only by the traces they leave behind as they pass through a detector. We cannot see them directly. In Davis’s experiment, these traces came in the form of atoms of the element argon, which were created when neutrinos collided with atoms of chlorine. Every so often the physicists would flush out the detector and count the number of argon atoms that had accumulated, deducing from this evidence how many solar neutrinos must have traversed the detector. Other experiments that used gallium rather than chlorine operated in a similar way: essentially visiting the beach now and then just to see if any additional footprints had been made.

A different approach was taken by the Kamiokande experiment—and subsequently by Super-Kamiokande—which was able to view the neutrino “footprints” as they were being made. In these experiments, the detectors were made primarily of water, but rather than changing the atoms of water into something else, neutrinos scattered their electrons in the same way that one billiard ball collides with another. Each time this happened, the scattered electron produced a cone-shaped flash of blue light called Cerenkov light, which was quickly converted into electrical signals by photon detectors placed outside the water volume.

The footprint metaphor however fails to highlight the most critical problem of neutrino detection. Neutrino interactions with matter are so weak that the chances of a footprint occurring are incredibly small; a typical neutrino can travel easily through a light year’s worth of lead. But rather than changing the atoms of water into something else, neutrinos scattered their electrons in the same way that one billiard ball collides with another. Each time this happened, the scattered electron produced a cone-shaped flash of blue light called Cerenkov light, which was quickly converted into electrical signals by photon detectors placed outside the water volume.

The footprint metaphor however fails to highlight the most critical problem of neutrino detection. Neutrino interactions with matter are so weak that the chances of a footprint occurring are incredibly small; a typical neutrino can travel easily through a light year’s worth of lead. Even then, every so often—essentially just by accident—one does collide with something, such as a chlorine atom in Davis’s experiment or an electron in the Super-Kamiokande experiment. To increase the chances of observing neutrinos, a detector must therefore contain lots of material—lots of chlorine or lots of electrons, for example—thus giving the neutrinos many opportunities for an accidental collision. Solar neutrino detectors therefore tend to be very big: the Super-Kamiokande experiment, for example, holds over 50,000 tons of water.

There is one further difficulty in trying to detect neutrinos from the Sun. To return one last time to our invisible man, imagine that the beach is crowded with swimmers and sunbathers each of whom also leaves footprints. Trying to figure out which footprints are meaningful (especially given that the number made by the other beachgoers is far larger than those made by our invisible stroller) is an extremely difficult task. Cosmic rays are one example of this problem, since they can create Cerenkov light in the same way neutrino interactions do. And we are being bombarded by cosmic rays all the time: if each cosmic ray were a raindrop hitting the surface of the Earth, we would be soaked by a steady downpour amounting to about one inch every few hours. The bottom of a mine is therefore an ideal place to study neutrinos because most cosmic rays are stopped by the rock before they reach the detector, while neutrinos are unaffected. To solar neutrinos, a kilometer of rock hardly matters at all, nor do the thousands of kilometers below the detector through which they travel upward during the night.

The Sudbury Neutrino Observatory uses the same basic technique as the Kamiokande experiments—looking for Cerenkov light produced by neutrinos interacting in water. A total of 7000 tons of water sits in a cavern 22 m wide by 34 m high, carved out of rock 2000 m beneath the surface of INCO Ltd.’s Creighton
Mine in Sudbury, Ontario (see illustration on page 18). At SNO’s depth—deeper than any other solar neutrino experiment—only three cosmic rays pass through the detector each hour. The Cerenkov light created by the neutrino interactions is detected by an array of 9500 photomultiplier tubes (PMTs), each capable of registering a single photon of light. This sensitivity to single photons is necessary because a neutrino event typically produces only 500 photons. The PMTs are supported by a stainless steel geodesic sphere 17.8 m in diameter.

Nested inside the PMT support sphere is a second sphere 12 m in diameter, built from 5.5-cm thick transparent acrylic. This vessel and its contents are what makes SNO unique: rather than holding ordinary water, which has two hydrogen atoms bound to one oxygen atom (H₂O), the acrylic vessel holds 275,000 gallons (1000 metric tons) of heavy water, which has two deuterium atoms bound to one oxygen atom (D₂O). Deuterium is the same as hydrogen in all respects except that it has a proton and a neutron in its nucleus (called a deuteron). It is this extra neutron that allows SNO to distinguish different types of neutrinos and thus determine whether there are neutrinos other than electron neutrinos reaching Earth from the Sun.

Cosmic rays are not the only source of false signals that SNO has been designed to avoid. Just about any material one can find on Earth—water, steel, mine dust—has a tiny amount of naturally occurring radioactive contamination. These radioactive nuclei produce charged particles that can generate the same