California
Institute of
Technology

E&S

Engineering and Science

Volume LXVI,
Number 1,
2003

In this issue

Voyaging across the Heliopause

Running on Fuel Cells

Looking over Technologies

This could be the prototype of the gas station of the future: the hydrogen-refueling station at Honda America in Torrance, where the Honda FCX (for fuel-cell experimental vehicle) leased by the city of Los Angeles goes to top off. Fuel cells combine hydrogen and oxygen to make electricity and water, and already provide nonpolluting power for everything from laptops to apartment buildings. Here, the hydrogen is made by splitting water molecules using energy from the solar panels visible just up the road, which are capable of filling the FCX's fuel tank once a day. The FCX gets 220 miles to the tank, enough for quite a bit of running around. For more on how Caltech research could lead to a greener future, see the story on page 18.

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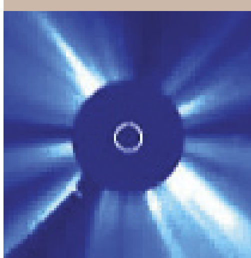

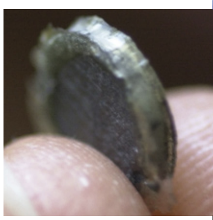

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On the cover: A bow shock (the crescent-shaped feature in the center) forms in the interstellar wind as it collides with an invisible astrosphere, or bubble, surrounding a young star in the nearby Orion Nebula. Another bow shock can be seen at upper right in this Hubble Space Telescope image from a year ago. On page 10, Ed Stone describes the bubble around our own sun and the Voyagers' coming encounter with its outer edge.

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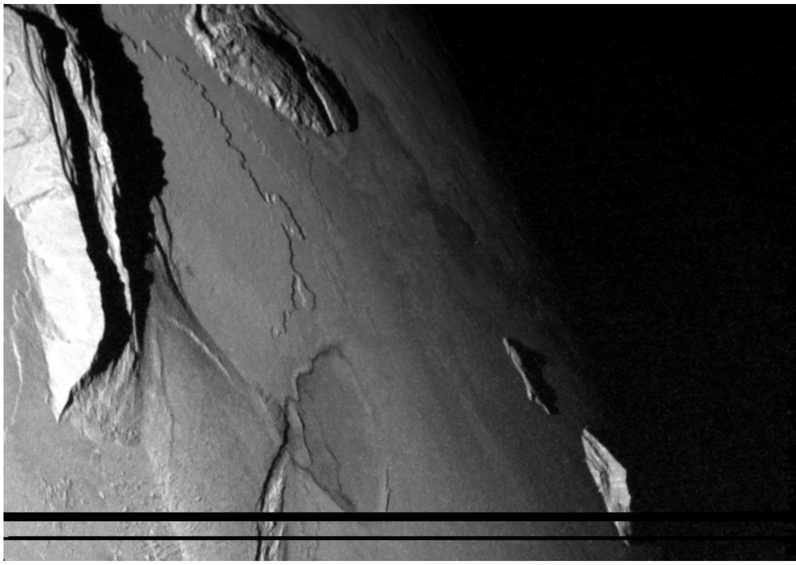


Requiem for a Heavyweight

Image credits: NASA, JPL, University of Arizona, University of Colorado

Above: This close-up of Europa combines data from two flybys in 1998 and 1996. The reddish "freckles" and the shallow pits are each about 10 kilometers across. Taken together, they suggest that Europa's icy crust may be churning away like a lava lamp. The pits may mark where cold surficial ice is sinking, while the ruddy ice may be upwelling from the interior. If Europa really does have a liquid ocean beneath, samples from these colored spots could provide clues to its composition, and perhaps even signs of life.

Above, right: In this shot of Io from Galileo's February 2000 pass, the setting sun casts surface features into sharp relief. At left is Mongibello Mons, seven kilometers tall, or three-quarters the height of Everest. By contrast, the scarp emerging from Mongibello's shadow near the top of the image is a mere 250 meters high. Few of Io's mountains look like Earthly volcanoes, and are instead thought to be blocks of crust uplifted along thrust faults—picture the San Gabriel mountains behind Pasadena on an enormous scale. The rise beyond Mongibello appears to be an older, worn-down mountain.

Galileo's long journey is nearly over. Its tape recorder's final playback ended successfully on February 28, returning data from its closest-ever pass by Jupiter on November 5, when it flew by the moon Amalthea and through part of Jupiter's gossamer ring. But alas, in order to ensure that the high-priority magnetic-field and dust-particle data were returned successfully, no pictures were taken.

The maneuvering propellant is almost exhausted after 14 years in space, seven of them orbiting Jupiter. So before Galileo's handlers lose the ability to steer it, it was set on a course that will plunge it into the giant planet's crushing atmosphere on September 21. This was done to ensure that the moon Europa, whose icy crust may hide an ocean of liquid water that might conceivably harbor life, is not contaminated by some future collision with the spacecraft. (Galileo was not sterilized as rigorously as the Mars explorers are—who knew?)

Designed, built, and flown by JPL, which Caltech runs for NASA, and launched from the space shuttle *Atlantis* in October 1989, Galileo was to explore the Jovian system for two years. The mission was so successful it was extended three times, returning about 14,000 shots from the main camera plus a host of other data and making innumerable discoveries, many of which have been chronicled in past Random Walks.

Along the way, Galileo took punishment that makes what happened to Arnold Schwarzenegger in the first *Terminator* movie look pretty tame. From the stuck high-gain antenna to a balky tape recorder to cumulative radiation doses more than four times what it was designed to withstand, the doughty spacecraft and its indefatigable, ingenious controllers soldiered on.

As it will continue to do. The magnetometer will saturate about an hour and a half before impact, but the other fields and particles instruments will try to keep returning real-time data "right to the bitter end," says sequence integration engineer Bruce McLaughlin (BS '77), until Galileo passes out of sight behind Jupiter with seven minutes and ten seconds to go. "The remaining few minutes of the craft will be spent in darkness, and alone...." A moment of silence, if you please. ☐—*DS*

The Sporting News

You wouldn't expect it from balmy, palmy Caltech, but we have the Pacific Regional Collegiate Figure Skating champions right here on campus. Emily Schaller, Kelly Martin, Lara Pruitt, and Olga Kowalewsky edged out Stanford by two points to advance to the national championships in Denver.

The team is so new they don't even have a coach, but rely on one another instead. Schaller, a grad student in planetary science and a Vermont native, had seriously considered a skating career but decided at age 13 to forego the day-long practices and special schooling for "a normal life." Kowalewsky, an aeronautics grad student, was an accomplished skater during childhood who has only recently returned to the rink. And freshman Pruitt spent high school sewing costumes and teaching group lessons in exchange for ice time and coaching, eventually becoming a registered U.S. Figure Skating Association coach.

At the nationals, Caltech faced stiff competition from such cold-weather schools as Dartmouth (whose team Schaller helped found as an undergrad), the University of Delaware, Cornell, Miami University of Ohio, Michigan State, and Western Michigan. A team usually fields up to 20 skaters and the sum of their scores determines its standing, so each of the Caltech foursome had to enter as many events as she possibly could. Despite the odds, the squad placed sixth over all, with Martin tying for first in upper-division ice dancing, Schaller winning a lower-level ice dance, and Schaller and Martin finishing third in their short programs.

In other championship seasons, the Caltech chess team (founded last fall) won the U.S. Amateur Team West Chess Championship. Postdoc Wei Ji Ma, freshman Eugene Yanayt, junior Graham Free, and freshman Zhihao Liu thus became the first collegiate team to do so in recent history. Then freshman Patrick Hummel, Ma, grad student Sergiy Vasylkevych, Yanayt, Free, Liu, and frosh Stuart Ward and Clark Guo trounced That Other Institute of Technology, 5-3, over the Internet. And having won the west, the Techers faced favored University of Texas, Dallas for the national championship in an Internet showdown on March 17. Caltech bounced back from two early losses to a 2-2 tie and then tied the playoff, forcing a second playoff that turned into a nail-biter: with less than 30 seconds left on the clock and another tied score, Ma found the move that won the championship.

And finally, senior Nathan Paymer and freshmen Jacob Burnim and Adam D'Angelo were one of 70 teams (from an initial field of 3,850 worldwide) to advance to the finals of the Association for Computing Machinery's International Collegiate Programming Contest, held March 22–25 in Beverly Hills. Sponsored by IBM, the contest consisted of 10 real-world programming problems to be solved within five hours. Each team has only one computer to work with, and the team that solves the most problems in the fewest attempts in the least time is the winner. The Techers finished 13th overall, and were the top-placing team from North America. □

From left: Olga Kowalewsky (kneeling), Emily Schaller (behind her), Lara Pruitt, and Kelly Martin (kneeling).

Is Great-Grandma a Mutant?

"A very short one."

— Jeanne Louise Calment, of France, then the oldest known living person, when asked what sort of future she anticipated having. *Newsweek*, March 6, 1995.

Even though Mme. Calment died in 1997 at the age of 122, we envy her longevity. Better, perhaps, to envy her mother's lineage, suggest Caltech scientists. A study of unrelated people who have lived for a century or more found that they were five times more likely than the general population to have a certain mutation in their mitochondrial DNA (mtDNA). This mutation may provide an advantage by speeding mtDNA's replication, thereby increasing its amount or replacing that portion of it that has been battered by the ravages of aging. The study was conducted by postdocs Jin Zhang, Jordi Cayuela, and Yuichi Michikawa; Jennifer Fish, a research scientist; and Giuseppe Attardi, the Steele Professor of Molecular Biology; along with colleagues from the Universities of Bologna and Calabria in Italy, and the Italian National Research Center on Aging.

The mitochondria are the "powerhouses" of the cell and have their own DNA, leading researchers to believe they were once independent organisms that were long ago assimilated. Mitochondrial DNA passes only from mother to offspring, and every human cell contains hundreds, or, more often, thousands of mtDNA molecules. It's known that mtDNA has a high mutation rate, and that such mutations can be harmful, beneficial, or neutral. In 1999, Attardi and colleagues found what Attardi described as a "clear trend" in the number of mtDNA mutations in individuals over the age of 65—in fact, in the skin cells the researchers examined, they found that up to 50 percent of the mtDNA molecules had been mutated. (See *E&S*, 1999, No. 4.) In another study two years ago, Attardi and colleagues found four centenarians who shared a genetic change in the so-called main control region of mtDNA. Because this region controls DNA replication, that observation raised the possibility that some mutations may extend life.

Now, by analyzing mtDNA isolated from a group of Italian centenarians, the researchers have found a common mutation in the same main control region. Looking at mtDNA in white blood cells of a group of 52 Italians between the ages of 99 and 106, they found that 17 percent had a specific mutation called the C150T transition. That frequency compares to only 3.4 percent of 117 people under the age of 99. To probe whether the mutation is inherited, the team studied skin cells collected from the same individuals between 9 and 19 years apart. In some, both samples showed that the mutation already existed, while in others, it either appeared or became more abundant during the intervening years. These results suggest that some people inherit the mutation from their mother, while others acquire it during their lifetime.

"We found the mutation shifts the site at which mtDNA starts to replicate, and perhaps that may accelerate its replication, possibly allowing the lucky individual to replace damaged molecules faster," Attardi says, adding that the study is the first to show a robust difference in an identified genetic marker between centenarians and younger folks. Their next goal, he says, is to find the exact physiological effect of this particular mutation.

The Italian contributors to the paper were Massimiliano Bonafe, Fabiola Olivieri, Giuseppe Passarino, Giovanna De Benedictis, and Claudio Franceschi. It appeared in the February 4 issue of the *Proceedings of the National Academy of Sciences*, and online at http://www.pnas.org. □—*MW*

Paged By a Gamma-Ray Burst

Scientists "arriving quickly on the scene" of an October 4 gamma-ray burst have seen, for the first time, that fresh energy continued to stoke its afterglow for more than half an hour after the initial explosion. The blast was first detected by NASA's High-Energy Transient Explorer (HETE) satellite, and follow-up observations were quickly undertaken by fast-thinking researchers around the globe, who report in the March 20 issue of *Nature*. The findings support the "collapsar" model of gamma-ray bursts, in which they are emitted after the core of a star 15 times more massive than the sun collapses into a black hole. "If a gamma-ray burst is the birth cry of a black hole, then the HETE satellite has just allowed us into the delivery room," said Derek Fox, a Caltech postdoc and lead author of the *Nature* paper. Fox discovered the afterglow using the Oschin 48-inch telescope located at Caltech's Palomar Observatory.

Gamma-ray bursts shine hundreds of times brighter than a supernova, or as bright as a million trillion suns. The mysterious bursts are common, yet random and fleeting. The gamma-ray portion of a burst typically lasts from a few milliseconds to a couple of minutes. An afterglow, caused by shock waves from the explosion sweeping up matter and compressing it until the heat makes it glow, can linger for much longer, releasing energy in X rays, visible light, and radio waves.

This gamma-ray burst, called GRB021004, appeared on October 4, 2002, at 8:06 a.m. EDT. Seconds after HETE detected the burst, its coordinates were downlinked to computers at NASA's Goddard Space Flight Center that generated an e-mail to a list of observatories around the world, including Palomar. Fox pinpointed the afterglow from images captured by the Oschin Telescope within minutes of the burst, and notified the astronomical community by e-mail. Then the race was on, as scientists in California, across the Pacific, Australia, Asia, and Europe employed more than 50 telescopes to zoom in on the afterglow before the approaching sunrise.

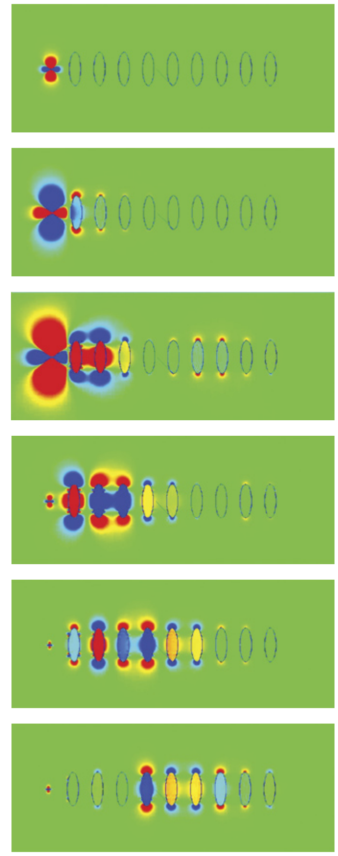
At about the same time, the afterglow was detected by the Automated Response Telescope (ART), a 20-centimeter instrument located in a Tokyo suburb and operated by the Japanese research institute RIKEN. ART started observing the region a mere 193 seconds after the burst, but it took a few days for these essential observations to be properly analyzed and distributed.

The combined observations revealed "flickers" that hinted that energy was still being injected into the afterglow well after the burst occurred. According to Shrinivas Kulkarni, the MacArthur Professor of Astronomy and Planetary Science and a co-author of the *Nature* paper, this power must have been provided by whatever object produced the gamma-ray burst itself. "This ongoing energy shows that the explosion is not a simple, one-time event, but that the central source lives for a longer time. This is bringing us closer to

Diffraction Unlimited

Four hundred years ago, a scientist could peer into one of those newfangled optical microscopes and see microorganisms, but nothing much smaller. Nowadays, a scientist can look in the latest generation of lens-based optical microscopes and also see, well, microorganisms, but nothing much smaller. The limiting factor has always been diffraction, a fundamental property of the wave nature of light, which fuzzes out images of objects much smaller than the wavelength of the light that illuminates them. Diffraction also hampers the ability to make and use optical devices that are less than a wavelength in size. Now Harry Atwater, the Hughes Professor and professor of applied physics and materials science, and his associates have created the world's smallest "light pipe"—a chain of several dozen submicroscopic metal slivers along which light "hops" in defiance of the diffraction limit.

Called a plasmon waveguide, the device consists of a glass slide with a thin metal coating on its surface. The metal was etched away to form a series of nanoparticles, each about 30 nanometers (30 billionths of a meter) in width, 30 nanometers in height, and 90 nanometers in length, lying parallel to one another like railroad ties. The space between the ties is so tiny that light energy moves from one to the next with very little radiated loss. The nanoparticles themselves are some 20 to 30 times smaller than the wavelength of visible light, so the energy moves between them by a

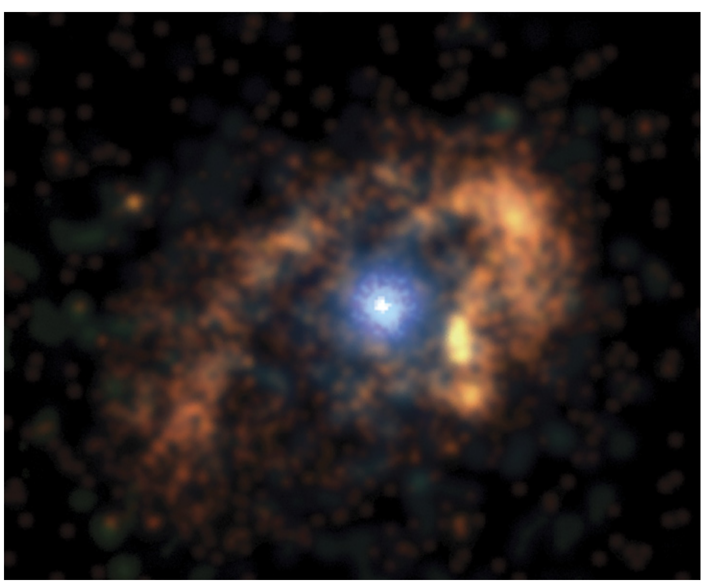


Above: These frames from an animation of a plasmon propagating between nanoparticles don't do justice to the truly trippy movies available at http://daedalus.caltech.edu/research/nanophotonics.html. Check 'em out!

a full understanding of these remarkable cosmic flashes." Added Fox, "We used to be impressed by the energy release in gamma-rays alone. These explosions appear to be more energetic than meets the eye."

Later radio observations at the Very Large Array in New Mexico, Caltech's Owens Valley Radio Observatory, the IRAM millimeter telescope in France, and elsewhere lend further support to the idea that the explosions continued increasing in energy. "Whatever monster created this burst just refused to die quietly," said co-author Dale Frail, a staff astronomer at the Very Large Array.

In 2001, a team of JPL astronomers led by Steven Pravdo refurbished and fully automated the Oschin Telescope, adding the Near Earth Asteroid Tracking (NEAT) camera. Although intended to hunt for asteroids that might one day hit Earth, the robotic system has helped to identify fully 25 percent of the gamma-ray burst afterglows discovered worldwide since the fall of 2001, when Fox wrote some software for the telescope. □—*RT*



Left: Eta Carinae shines five million times brighter than the sun, and is boiling matter off its surface at a prodigious rate—the feather boa in this X-ray image is about two light years across and is made of gas heated to about 3,000,000°C—causing some astronomers to think it could go supernova any day now. Since it's 7,000 light years from Earth, we needn't worry about the sunburn, but it would be an awesome spectacle.

process known as dipole-dipole coupling, which propagates considerably more slowly than does light in a vacuum. And dipole-dipole coupling is omnidirectional, so light in the waveguide can negotiate 90° turns with ease.

Because the era of nanoscale devices is rapidly approaching, Atwater says, the future bodes well for extremely tiny optical devices that, in theory, would be able to connect to molecules and someday even to individual atoms. Individual transistors on a microchip are already too small to be seen in a conventional optical microscope, so plasmon waveguides could be used as optical interconnects. And metal nanoparticles are known to interact with biomolecules, so a virus or even a single molecule of nerve gas could conceivably be detected.

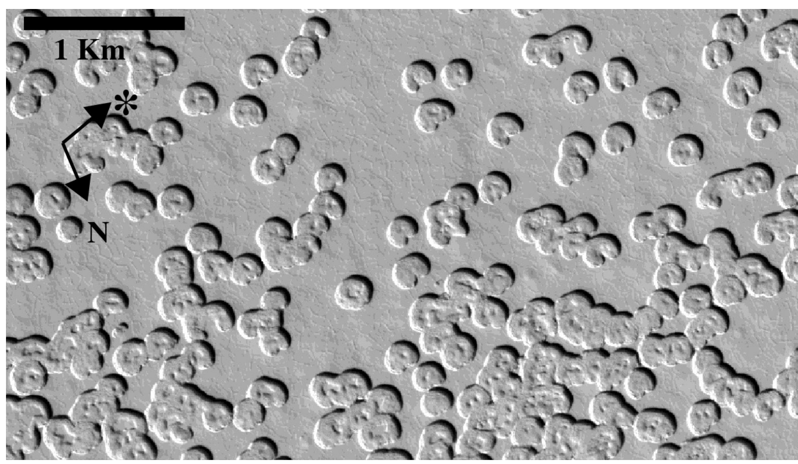
A description of the device will appear in the April 2003 issue of *Nature Materials*. Besides Atwater, the other Caltech authors are postdocs Stefan Maier (MS ’00, PhD ’03), who was responsible for the working device, and Pieter Kik. Other authors were Sheffer Meltzer, Elad Harel, Bruce Koel, and Ari Requicha, all from the University of Southern California. The waveguides were fabricated at JPL’s electron-beam lithography facility with the help of JPL employees Richard Muller, Paul Maker, and Pierre Echternach. The work was sponsored by the Air Force Office of Scientific Research, with additional support by grants from the National Science Foundation and Caltech’s Center for Science and Engineering of Materials. —*RT*

Swiss Cheese and Cold Drinks

For future Martian astronauts, finding a plentiful water supply may be as simple as grabbing an ice pick and getting to work. Caltech planetary scientists think that Mars’s polar residual caps are made almost entirely of water ice—with just a smattering of frozen carbon dioxide, or “dry ice,” at the surface. Reporting in the February 14 issue of *Science*, Professor of Planetary Science Andrew Ingersoll and grad student Shane Byrne (MS ’01) present evidence that the decades-old model of the polar caps being made of dry ice is in error. The model dates back to 1966, when the first Mars spacecraft determined that the Martian atmosphere was largely carbon dioxide. Later observations by the Viking spacecraft showed that the north polar cap consisted of water ice underneath a dry-ice covering, but experts continued to believe that the south polar cap was made of dry ice.

However, high-resolution images from the Mars Global Surveyor show that most of the south polar residual cap resembles Swiss cheese—pocked with flat-floored, circular pits some eight meters deep and 200 to 1,000 meters in diameter that grow outward (but not downward) by about one to three meters per year. And infrared

Right: Earth’s moon may be made of green cheese, but parts of Mars’s south polar cap look more like a slice of Swiss. In the upper image, N stands for north and * indicates the direction to the sun. The fact that all the “holes” are roughly the same size indicates they all started growing at roughly the same time. The lower image of a typical hole shows its flat floor, steep walls with hints of collapse debris, and a prominent cusp on the north, or less lit, rim—a strong hint that sunlight is at the root of the hole’s formation. The adjoining shallow depression may be a hole in the making.



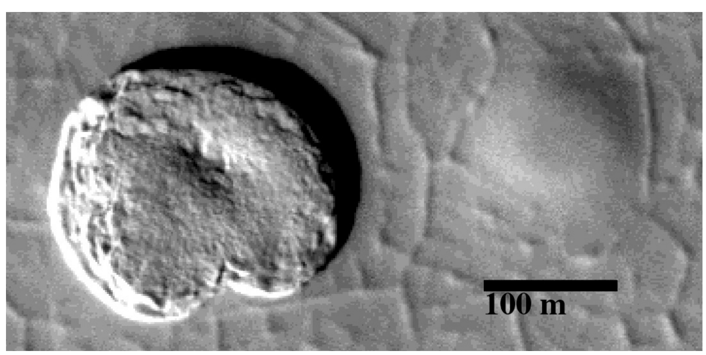


Image credits: NASA, JPL, Malin Space Science Systems measurements from the newly arrived Mars Odyssey show that the pit floors heat up during the Martian summer. Water ice, which is well below its freezing point, would be expected to get warmer as the summer progresses. But dry ice freezes at a lower temperature and in summer reaches the point at which it sublimes, or turns straight into a gas. It then remains at the sublimation temperature until it's all gone. So Byrne (the lead author) and Ingersoll concluded that the pitted layer is dry ice, but that the floor material, which makes up the bulk of the polar cap, is water ice. Thus the south polar cap is actually similar to its northern counterpart, which Viking data showed loses its one-meter covering of dry ice each summer, exposing the water ice underneath. But the south pole's eight-meter dry-ice cover is too thick to disappear entirely.

Although we may not be obliged to haul our own water to the Red Planet, the news is paradoxically bad for the visionary plans often voiced for "terraforming" Mars in the distant future, Ingersoll says. "Mars has all these flood and river channels, so one theory is that the planet was once warm and wet." Injecting a large amount of carbon dioxide into the atmosphere would create a "greenhouse effect," capturing enough solar energy for liquid water to exist. "If you wanted to make Mars warm and wet again, you'd need carbon dioxide, but there isn't nearly enough if the polar caps are made of water."

The new findings also pose the question of how Mars could have been warm and wet to begin with. People had assumed that there was once enough carbon dioxide in the atmosphere to keep the planet warm, but now there's simply not enough carbon dioxide at the poles for this to clearly have been the case. "There could be other explanations," Byrne says. "It could be that Mars was a cold, wet planet." Water could have flowed underneath an insulating layer of ice to form the channels and other erosion features we see today. Then, perhaps, the ice sublimed away, to be eventually redeposited at the poles.

And planetary scientists have assumed that Earth, Venus, and Mars are similar in their total carbon dioxide content, with Earth having most of its carbon dioxide locked up in marine carbonates and Venus's carbon dioxide causing a runaway greenhouse effect. But eight meters' worth of polar ice amounts to only a small fraction of the carbon dioxide found on Earth and Venus. So finding Mars's missing carbon dioxide, or accounting for its absence, will now be a major goal. □—*RT*

A Mars Orbiter Camera image (top) and a THEMIS temperature map of the same area. The difference between blue and red is about 10°C or 20°F, a significant spread, and the warmer areas correspond to the pit floors. But if all the visible surfaces were dry ice, the temperatures would be uniform.

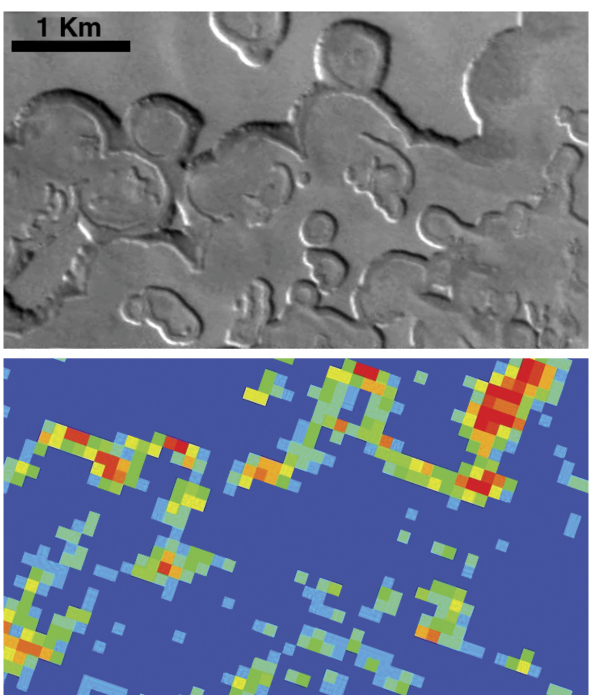


Image credits: NASA, JPL, Malin Space Science Systems, Arizona State University

S. Low Networks for FAST Data Rates

Caltech computer scientists have developed an Internet data-transfer protocol fast enough to download a full-length DVD movie in less than five seconds. Called FAST, for Fast Active queue management Scalable Transmission control protocol, it achieved a speed of 8,609 megabits per second in the presence of background traffic by using 10 simultaneous data flows. The FAST protocol was developed in Caltech's Networking Lab, led by Steven Low, associate professor of computer science and electrical engineering, and is based on theoretical work done in collaboration with Caltech's John Doyle, a professor of control and dynamical systems, electrical engineering, and bioengineering; and Fernando Paganini, an associate professor of electrical engineering at UCLA.

The experiment was performed last November during the Supercomputing Conference in Baltimore, by a team from Caltech and the Stanford Linear Accelerator Center, in partnership with the European Organization for Nuclear Research (CERN), DataTAG, StarLight, TeraGrid, Cisco, and Level(3). Commercial, off-the-shelf hardware and applications were used, as were standard Internet packet sizes. The key was modifying a ubiquitous piece of software called Transmission Control Protocol, or TCP, on the computer sending the data.

TCP, which manages traffic flow on the Internet and attempts to minimize congestion, was designed in 1988 when the 'Net could barely carry a single uncompressed telephone call. TCP cannot be scaled to meet anticipated needs, and interim remedies such as using nonstandard packet sizes or aggressive algorithms (which can monopolize network resources to the detriment of other users) have proven ineffective, or are difficult to deploy.

With Internet speeds doubling roughly annually, the performances demonstrated by this collaboration are likely to become commonly available in the next few years. □—*RT*

New Science or Old Math?

Stephen Wolfram (PhD '80), a 1981 MacArthur Foundation "genius" and the creator of the technical-computing software system *Mathematica*, spoke to a packed Beckman Auditorium on Saturday, February 1, about his book *A New Kind of Science*. He then engaged in an occasionally spirited discussion with a panel of cordial yet skeptical Caltech faculty members, after which he took questions from the floor.

According to Wolfram, his book represents 20 years of study and experiment, with about a decade of that going into the actual writing. Beginning with the discovery that computer programs carrying out simple rules over and over and over again—"cellular automata," which have been known since the 1950s—could produce extremely complex behavior, he came to the conclusion that the iteration of simple rules can describe the workings of the natural world more successfully than can the often complex mathematical equations used by science up until now. He illustrated his thesis with numerous computer-generated images of complex patterns produced by simple rules, which he compared to similar patterns from nature: the forms of snowflakes, the markings on seashells, the veining of leaves, and even the evolution of the universe. He averred that much of nature represents the same level of computational complexity as do human beings, though the human race remains unique through its own history of effort and development.

The panel comprised Christoph Adami, faculty associate in computation and neural systems and director of the Digital Life Laboratory at Caltech, as well as principal scientist in JPL's quantum technologies group; John Preskill, the MacArthur Professor of Theoretical Physics and director of the Institute for Quantum Information; David Stevenson, the Van Osdol Professor of Planetary Science; and Steven Koonin (BS '72), Caltech's provost and a professor of theoretical physics, who moderated. Much of the discussion revolved around whether or not Wolfram's work is genuinely science. Preskill, for instance, while granting that *A New Kind of Science* works well as science writing, was less sure of its usefulness for scientists, and Stevenson pointed out that one of the rules of "old" science is the production of testable predictions, of which he found in Wolfram's book "not one." Wolfram demurred, maintaining that his book is concerned with basic issues, not specific applications, and that his ideas are closer to those of mathematics and the biological sciences than to physics. In response to a question by Koonin, he suggested that his concepts would no more be proved right in a laboratory than would those of calculus. Preskill, while accepting that one of the many models computers could generate might fit reality, wondered whether that offers anything in the way of genuine explanatory power. Wolfram felt that it does, and that his concepts' potential to describe the natural world would allow one to generate testable predictions.

The most spirited exchange may have been with Adami, who stated that what biologists mean by complexity is very different from how Wolfram was using the term. Biologists deal with *functional* complexity: in cell division, metabolic processes, and other biological systems that have accumulated over billions of years of ensuring the survival of organisms in their environments. For such systems, he maintained, there is no single underlying rule that creates a pattern. Wolfram replied that it's dangerous to quote "what biologists think," since biology represents a wide spectrum of views.

Stevenson noted that, while Feynman diagrams—invented by the late Caltech professor of theoretical physics and Nobel laureate Richard Feynman as a way to visualize the interactions of atomic particles, and which a number of Wolfram's patterns rather resembled—improved physics computations, they didn't really change the underlying science, and wondered how Wolfram's approach was any different. While conceding that his ideas could be construed as a computational method if one wished, Wolfram insisted that they are more useful than traditional methods. When Preskill questioned how far scientists could actually get with them, saying that there was little in the chapter on physics that he could, as he put it, "get my hands on," Wolfram made the point that no one was going to know how his models would pan out until they had panned out.

Koonin wrapped up the discussion with a spot-on imitation of John McLaughlin of TV's *McLaughlin Group*, asking—"Yes or no!"—whether *A New Kind of Science* would be seen 20 years hence as a paradigm shift, that is, an event that transforms the way scientists view the world. None of the panelists thought so, and Koonin expressed the hope that they might be wrong, while Wolfram joked that he'd heard pretty much what he would expect to hear from scientists on the verge of such a shift. □—*MF*

The Literary Supplement

It's already been a banner year for distinguished authors on campus. The man who brought us *Prey*, *Jurassic Park*, *The Andromeda Strain*, and the Emmy-winning medical drama *ER*, Michael Crichton, gave the annual Michelin Lecture on January 17. "Do Aliens Cause Global Warming?" looked at scientists who publish results of dubious rigor in order to support political agendas.

On March 17, Oliver Sacks, the neurologist whose research inspired him to write *Awakenings,* which later became a movie starring Robin Williams and Robert DeNiro; and *The Man Who Mistook His Wife for a Hat*, a classic compendium of clinical stories; spoke on "Creativity and the Brain."

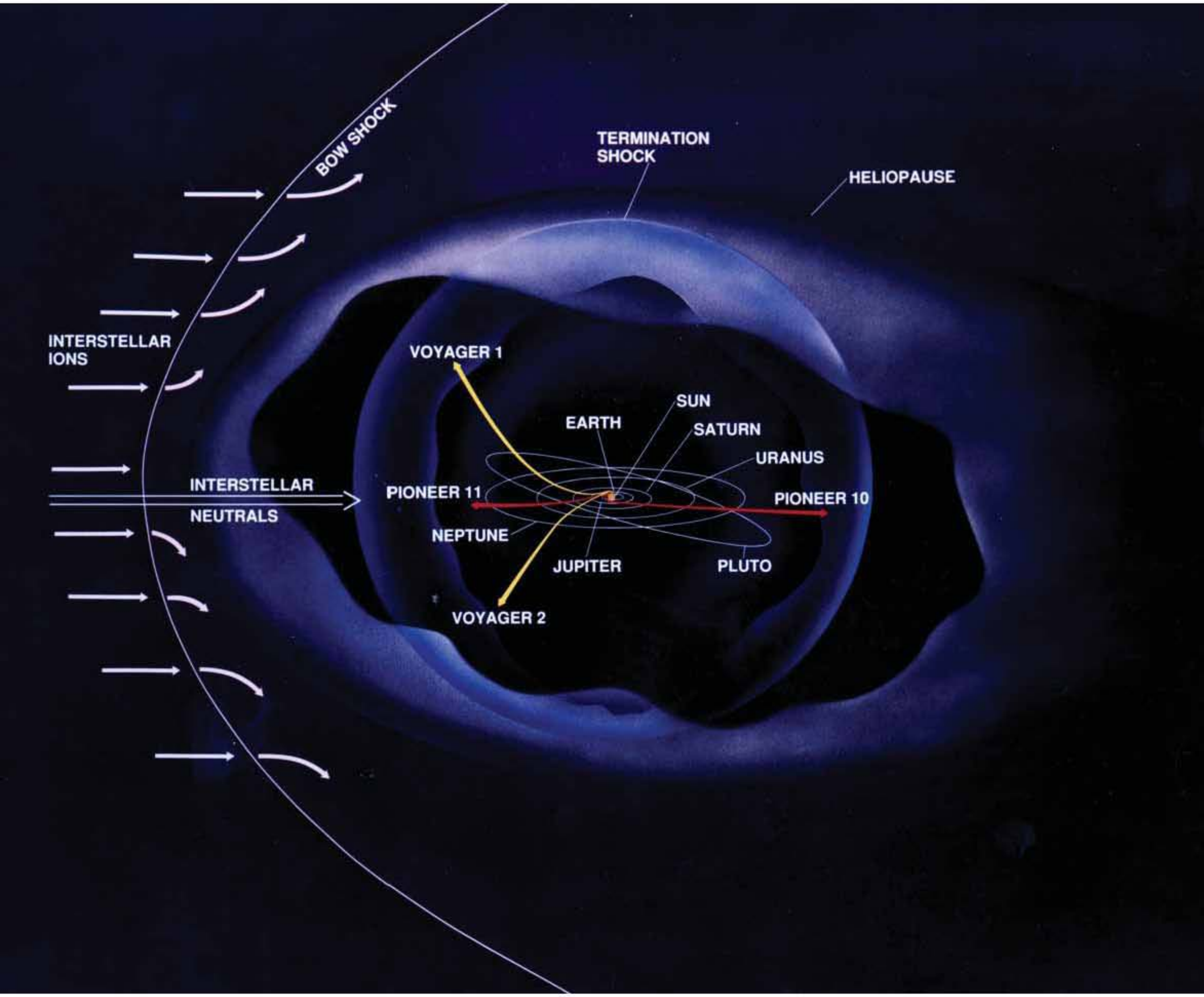
And physicist-cum-science-writer-and-novelist Alan Lightman (MS '73, PhD '74), author of *Ancient Light* and *Einstein's Dreams*, participated in several public events during his tenure as writer in residence, sponsored by Caltech's Words Matter project. □

Crichton lingered for quite a while afterward to give autographs and chat with fans.

Below: A flying tortoise? No, it's a 25,000-pound magnet being lowered into position in the Broad Center's basement, where the Magnetic Resonance Imaging lab will probe the neurological bases of activities such as reading, as well as such staples of great literature as jealousy, greed, and altruism. Volunteers will be needed, and you might even get a picture of your brain as a souvenir if you do.

Above: This origami frog, cast in bronze, adorns a drinking fountain in Santa Monica on the corner of Second Avenue and Santa Monica Boulevard. Four native critters designed by Robert Lang (BS '82, PhD '86), author or co-author of seven books on origami, were commissioned for the Third Street Promenade. But as Kermit might have said, "It's not easy being public art." The sea urchin and the garibaldi (a kind of fish) were removed by the city as being too pointy, and the dragonfly was stolen.

The two Voyagers are now headed to the outer edges of this bubble and then into interstellar space, where for the first time a spacecraft from Earth will be completely immersed in matter from stars other than the sun.



Voyager Journeys to Interstellar Space

by Edward C. Stone

Right: Both Voyager spacecraft were designed and built for NASA at the Jet Propulsion Laboratory and are also operated by the lab.

Left: Voyagers 1 and 2 will soon venture out of the heliosphere, the bubble created by the solar wind, and into interstellar space. Although the Pioneer spacecraft were launched earlier, the Voyagers are faster and will become our first interstellar probes. First they will cross the termination shock, where the solar wind slows from supersonic to subsonic speeds. Finding exactly where the termination shock is will allow researchers to estimate the current extent of the heliosphere and determine how much farther the spacecraft have to go to reach interstellar space.

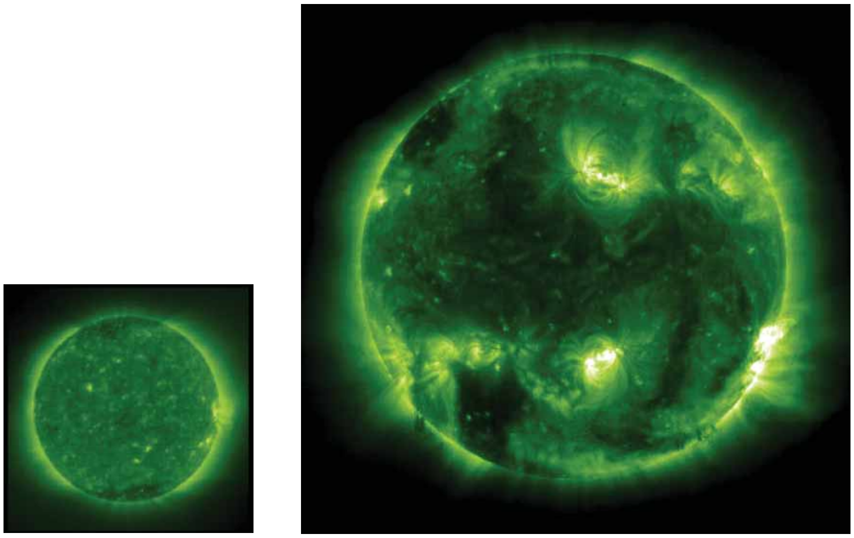
Twenty-five years ago we embarked on a journey of exploration that returned an unequaled wealth and diversity of discovery, a journey that continues as we search for the edge of interstellar space. We launched two Voyager spacecraft in August and September 1977, taking advantage of a special opportunity: once every 176 years Jupiter, Saturn, Uranus, and Neptune are in positions on the same side of the sun that allow a spacecraft to fly by all four. The 30-year journey to Neptune was shortened to only 12 by the slingshot boost from swinging by each of the planets along the way. We were fortunate that this opportunity occurred in the late 1970s. Ten years earlier, our technology would not have been ready, and a few years later, after the Space Shuttle era had begun, the launch vehicles we needed would have been retired.

During this journey, the Voyagers revealed the remarkable ways in which common geophysical processes produce diverse worlds: dozens of immense hurricane-like storms on Jupiter, of which the Great Red Spot is the largest, at two-to-three Earths across; the lava lakes and 50-mile-high volcanic plumes on Jupiter's moon Io, heated by the tidal flexing of its crust; the icy crust of Io's neighbor, Europa, the smoothest surface in the solar system; spiral waves in the rings of Saturn caused by tiny satellites and other moons shepherding kinked, narrow rings; Saturn's largest moon, Titan, with organic molecules raining on a surface obscured by a 200-mile-high haze layer; Uranus, tipped on its side with its magnetic pole near the equator, and its nine narrow, black rings; its small moon, Miranda, with one of the most geologically complex surfaces in the solar system; and finally Neptune, with the fastest winds, even though it is six times farther from the sun than Jupiter, with sunlight only 1/900th of what it is on Earth; and its moon, Triton, the coldest object in the solar system, with geysers erupting from its frozen-nitrogen polar caps.

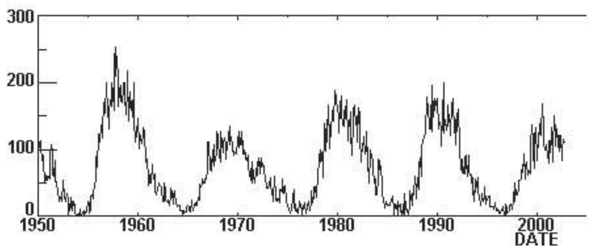
In 1989 Voyager flew by Neptune, completing an unprecedented decade of discovery. But the mission is not over. What lies beyond the giant outer planets? Voyager is still in the bubble of plasma, called the heliosphere, that surrounds the sun. (It's called an astrosphere around other stars.) The two Voyagers are now headed to the outer edges of this bubble and then into interstellar space, where for the first time a spacecraft from Earth will be completely immersed in matter from stars other than the sun.

A supersonic wind from the sun creates the bubble. The sun's visible surface is about 5,800 degrees C and has sunspots that mark the eruption of magnetic flux from deep inside. The sunspots are the visible indications of the polarity reversal of the solar magnetic field that occurs every 11 years. They tend to come in pairs, with their number varying over the 11-year cycle, seesawing from a period of maximum sunspot activity to one of minimum activity. A solar maximum occurred in 1980, again in 1990, and most recently in 2001.

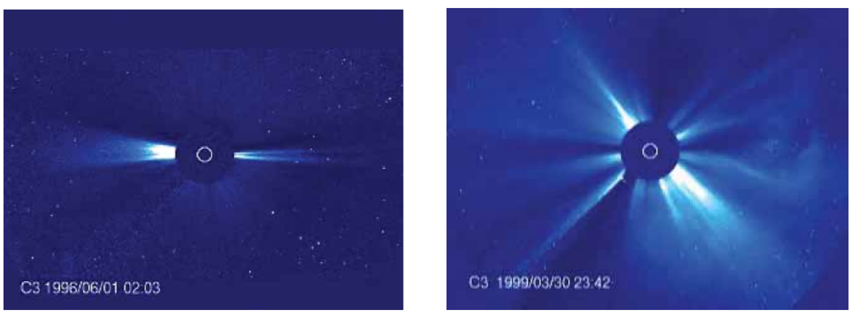
In the images of the corona shown in green on the next page, you can see the arches associated with magnetic fields looping from one region to



Over a cycle of 11 years, the sun goes from a period of minimum activity (December 1996, far left) through one of maximum activity (June 1999, left), characterized by a great increase in the number of sunspots, which are the surface expression of magnetic eruptions from deep inside the sun. These images in the extreme ultraviolet show the magnetic loops from sunspot to sunspot, mixing the magnetic fields and releasing the energy that heats the solar atmosphere and creates the hot plasma called the corona. There are darker regions, or "holes," in the corona (note particularly the polar holes at solar minimum), where the plasma is escaping.



The number of sunspots varies over an 11-year period.



Blocking the sun's light with a coronagraphic disk (the sun is the size of the small white circle in the center) reveals the brighter plasma trapped near the equator, while the solar wind escapes at 2 million mph through the darker coronal holes. At solar maximum (right) greater activity and magnetic complexity results in fewer magnetic holes in the corona; the solar wind, therefore, streams out more slowly at all latitudes.

another. Solar maximum, when there are many sunspots and magnetic loops, is on the right; if this were in motion, you would see it roiling and changing as the turbulent motions in the atmosphere mix the magnetic fields from nearby regions, causing them to merge and release energy. It is this magnetic energy that heats the extended solar atmosphere to create the corona, the bright plasma of over a million degrees surrounding the sun. There are darker "holes" in the corona where the plasma easily escapes along magnetic field lines that open out into interplanetary space. Because there is less material in coronal holes, there is less light from those regions.

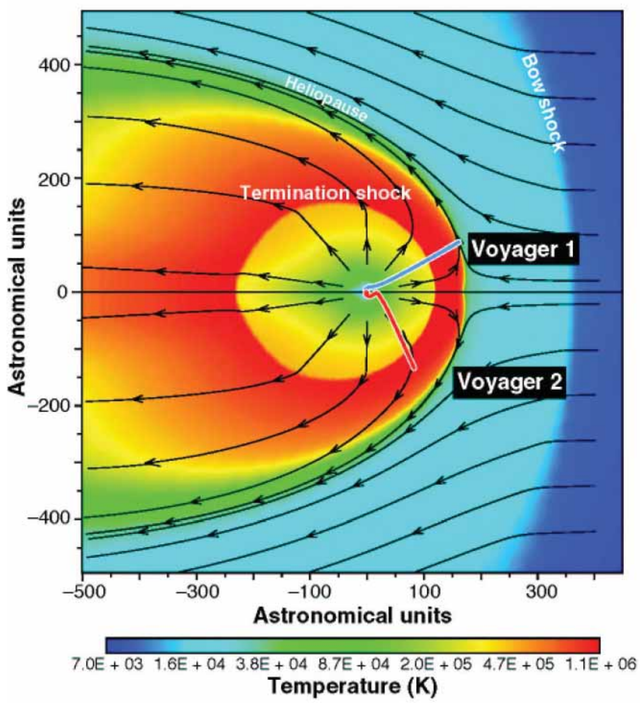
At solar minimum on the left, the corona is much simpler, with a large coronal hole in each polar region. Faint lines stream radially outward in the polar coronal holes where the plasma flows away from the sun at two million miles per hour. Wind speed is highest when the sun is quiet, while during active periods with many sunspots the corona is more turbulent and chaotic and the wind more variable, with speeds as low as only one million mph. That's a key factor that I'll come back to shortly.

Now let's look at the corona as it expands farther from the sun. In the blue images at left, the sun is the size of the small white circle and is blocked from view by a disk that creates an artificial solar eclipse. At the solar minimum in 1996 (on the left), there are bright regions near the solar equator where closed magnetic loops retain the coronal plasma, while at higher latitudes the wind streams away radially, filling up space at two million mph. But at solar maximum, on the right, the corona is quite different, with closed magnetic loops and bright regions at all latitudes. Because of the complex magnetic field associated with the increased solar activity, the darker regions corresponding to coronal holes are much more limited, and the wind streams outward more slowly.

The bubble that the solar wind creates around the sun changes size as the wind speed changes with solar activity. At solar minimum, the higher-speed wind creates a larger bubble than at solar maximum, when the winds are slower. Visual evidence of the solar wind can be seen with comet tails serving as wind socks. As a comet orbits the Sun, its tail always points away from the sun, blown outward by the solar wind.

The heliospheric bubble with the sun at its center is illustrated in the diagram on the opposite page, along with the Voyager trajectories. In the yellow area surrounding the sun, the temperature is about 250,000 degrees. The wind starts at a coronal temperature of more than a million degrees at the sun and cools as it flows outward. The density and pressure also decrease as the wind expands to fill an increasingly large volume. The outward expansion continues until the declining solar wind pressure is balanced by the inward

The bubble that the solar wind creates around the sun changes size as the wind speed changes with solar activity.



In the diagram above, the arrows indicate the flow of the solar wind (inside the bubble) and the interstellar wind outside. At the termination shock, the supersonic solar wind abruptly slows down, heats up to a million degrees, and then turns and flows down the tail of the heliosphere. Where the interstellar wind meets the heliopause, it's deflected around the heliosphere, which becomes a windsock indicating which direction the wind is blowing. A bow shock forms in front of the heliopause as the cold, supersonic interstellar wind slows down, warms up, and is deflected around the heliopause.

pressure of the interstellar wind of ions coming from the explosion of nearby stars. A boundary called the heliopause separates the two winds where they meet. The interstellar wind from the right in the figure flows around the heliosphere, deforming it into a wind-sock-like shape with a tail.

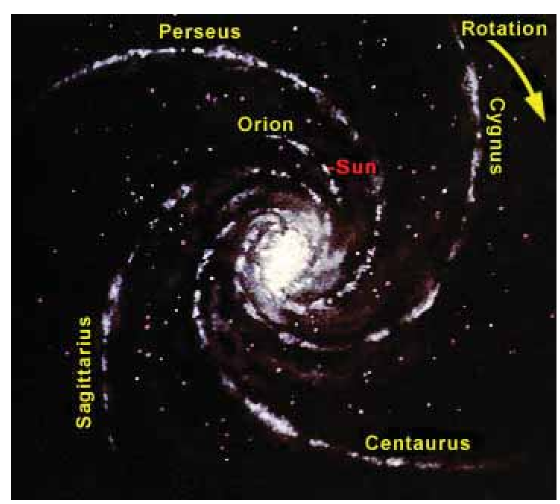
At over one million mph, the solar wind is supersonic, so it can't plunge directly into the boundary; just as a supersonic aircraft creates a shock (or sonic boom) in front of it, a shock forms where the solar wind abruptly slows to subsonic speeds as it approaches the heliopause. This is called the termination shock because it's the end of the supersonic flow of the solar wind. The wind slows from a million mph to 250,000 mph, and it becomes very hot (the red region) as the kinetic energy of the supersonic flow is converted into thermal energy in the subsonic wind. Beyond the termination shock, the subsonic wind slowly turns to flow down the heliospheric tail. As shown in the illustration, the interstellar wind is probably supersonic as well, so there is likely a shock out in front of the heliosphere called a bow shock.

What evidence do we have for bow shocks in front of other stars? The cover shows a very young star in a nearby star-forming region in the Orion nebula about 1,500 light years away. Although we can't see the astrosphere around the star, we know it is there because we *can* see that a bow shock (the vertical arc in the middle) has formed in the interstellar wind that blows from the center of the Orion nebula. This is the shocked gas that forms as the interstellar wind abruptly slows and is deflected around the astrosphere. Another smaller bow shock is at the upper right.

What about our own galactic neighborhood? What's outside the heliosphere? If we could look down on our galaxy (which of course we can't because we're in it), we would see the sun in one of the spiral arms called the Orion arm. We're about 26,000 light years from the center of the Milky

PICTURE CREDITS: 10, 11, 17 – NASA/JPL; 12 – SOHO, NASA/MSFC; 13, 16 – G. P. Zank; 15 – D. A. Gurnett & W. S. Kurth

Looking down on the Milky Way, we can locate our sun in the Orion arm spiraling out from the center of the galaxy, 26,000 light years away.



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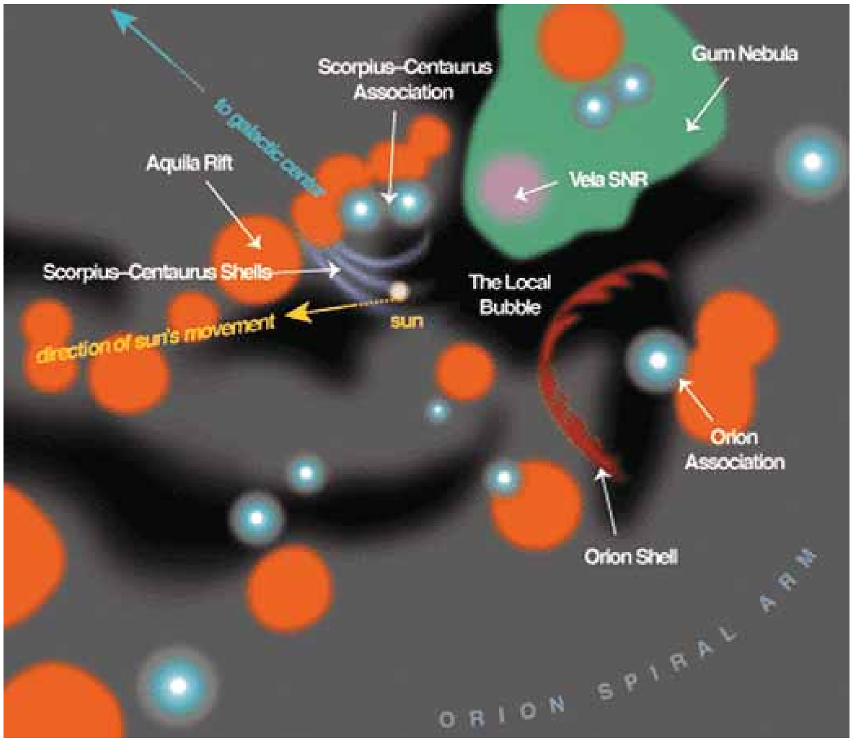


About 5 million years ago, a massive explosion in the Scorpius-Centaurus Association (about 400 light years away) sent waves of cooler, denser "shells," or "clouds," through the Local Bubble, in which our sun lives. The denser medium in the cloud compresses the heliosphere, making the heliopause closer and quicker for Voyager to reach. The orange blobs here are star-forming regions.

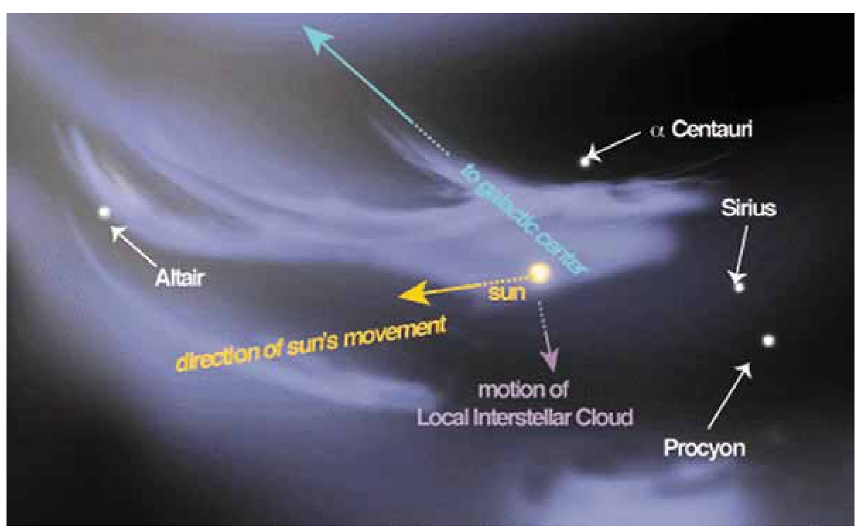
Way, about halfway out in the disk of the galaxy. In the drawing above, we zoom in closer to the Orion arm, to a scale of 1,500 light years across. The orange globs are stellar nurseries, dense molecular clouds that collapse to form stars. Near us, about 400 light years away, is a star-forming region called the Scorpius-Centaurus Association, where there was a great episode of star formation about five million years ago. At that time a massive star exploded, sending a shock wave through the molecular cloud, causing many new stars to form. The winds associated with that episode generated the "shells," or "clouds," that you can see here as blue arcs emanating from the Scorpius-Centaurus Association.

The black region in the drawing, called the Local Bubble, is very low density and very hot—about a million degrees. The shells, or clouds, are about 7,000 degrees, much cooler than the bubble that they're moving through. They're also denser than the bubble, but only relatively. "Denser" means that a cubic inch of cloud might contain 150 atoms, compared with the best laboratory vacuum, which would contain 10,000 times more. The Local Bubble is even more rarified, with less than one atom per cubic inch. Even though the interstellar medium is remarkably dilute, on a larger scale it behaves much like denser gases and fluids with which we are familiar.

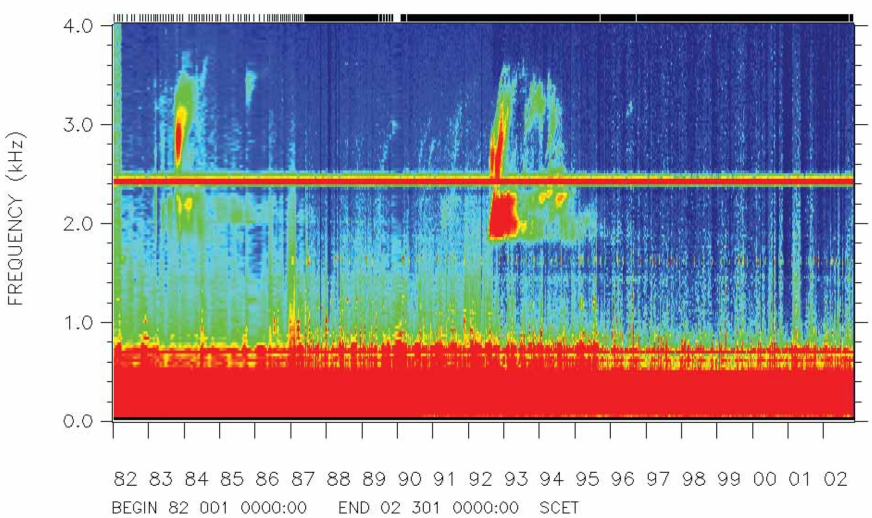
Now, the sun is moving relative to its surroundings. Actually, everything is orbiting the center of the galaxy, but if we neglect that and consider just the motion of the sun relative to everything around it, it's moving in the direction of the yellow arrow. If we zoom in even closer (below) and look at the local cloud, we can see that the sun is moving to the left in the image and the cloud is moving downward. It appears that the cloud enveloped the sun only in the last 1,000 to 100,000 years —in other words, very recently on a galactic time scale.

Before that, the sun was in the Local Bubble, where the interstellar pressure is much lower than in the cloud. As a result, the solar wind would have expanded much farther outward and the heliosphere would have been much larger than it is now. We're fortunate that we're in a dense

Because the sun is moving in the direction of the yellow arrow and the dense cloud that it's in is drifting toward the bottom of the image, the interstellar wind appears to be coming from the direction of the center of the galaxy. Fortunately, that's the direction the Voyager spacecraft are headed, which means they are on the shortest route out of the heliosphere.



We were fortunate that in 1977 the planetary alignment was on the side of the solar system toward that direction [toward the galactic center], because that means we are heading in the general direction of the nose of the heliosphere—the shortest way out.



These low-frequency radio signals from the heliopause were detected when huge blast waves from the corona at solar maximum excited the interstellar plasma in 1983 and 1992. By observing when the eruption blasted off from the sun, we can calculate how far it is to the heliopause. Cosmic rays are providing the essential clues.

cloud where the inward pressure makes the heliosphere smaller and the journey to the edge of interstellar space shorter.

The shortest distance to the heliopause is toward the nose of the heliosphere, that is, toward the incident interstellar wind rather than down the tail of the heliosphere. The combined motions of the sun and the dense interstellar cloud are such that the interstellar wind appears to be coming from the direction of the center of the Milky Way. We know the direction of the interstellar wind because, unlike interstellar ions that are deflected around the heliosphere, neutral atoms in the wind, such as hydrogen and helium, drift deep into the heliosphere where their arrival direction can be observed. We were fortunate that in 1977 the planetary alignment was on the side of the solar system toward that direction, because that means we are heading in the general direction of the nose of the heliosphere—the shortest way out.

Although we know the direction to the nose of the heliosphere, we don't know precisely how far away it is. John Richardson from MIT continuously measures the outward pressure of the solar wind very accurately, but the uncertainty in our knowledge of the inward interstellar pressure leads to an uncertainty in our estimate of the distance to the heliopause where the two pressures are in balance. Our current knowledge of the pressure in the local interstellar cloud suggests that the distance to the nose of the heliosphere is between 125 to 140 astronomical units (AU; one AU is the distance from the sun to Earth). Neptune is at 30 AU, so the heliopause is four to five times farther from the sun than Neptune. At the end of 2003, Voyager 1 will be 90 AU from the sun, and Voyager 2 will be 72 AU.

We can also estimate the distance to the heliopause by observing the speed of a blast wave from a coronal mass ejection and determining how long it takes the blast wave to reach the heliopause. When a large blast wave reaches the heliopause, it excites the interstellar plasma to radiate radio waves, which we can detect. Since we can observe when the blast wave starts at the sun, and we can determine when the radio waves begin, we can estimate the distance if we know the speed of the blast wave.

Don Gurnett and Bill Kurth at the University of Iowa observed such radio emissions in 1983, the first time radio emissions from the heliopause were detected. The frequency is so low (around 2,000 cycles per second) that the radio waves are undetectable inside of about 10 AU because they are excluded by the denser solar wind plasma closer to the sun.

It had been suggested by Ralph McNutt, then at MIT, that a major blast wave was responsible and that, since such large blast waves occur at solar maximum, such episodes should occur every 11 years during periods of maximum solar activity. When the investigators observed another episode in 1992, they looked for ways to determine the time it took the blast wave to reach the heliopause. When an eruption from the sun blasts out through the solar system, it sweeps out the cosmic rays that have come in from the galaxy. So there's a temporary decrease in cosmic radiation at Earth when the blast sweeps past; that tells us the start time. At Earth, we observed a major decrease in galactic ray intensity in 1982, and 412 days later the radio emission appeared in 1983.

In 1991, another major blast wave swept up the cosmic rays at Earth, and 419 days later another episode of radio emissions began. So that gives us the time. All we need to know is the speed of the blast wave. Although we can measure the speed of the blast wave out to Voyager's distance, we've never been to the very outer edges of the heliosphere, so we don't know how much the blast wave slows as it encounters the termination shock and continues through the hot, slow wind beyond the shock to the heliopause. That means there is uncertainty about the speed and therefore in the estimated distance to the heliopause. But the best estimates suggest that the average time of 415 days corresponds to a distance of 110 to 160 AU, which is similar to the estimate mentioned earlier—four to five times as far out as Neptune.

Another way to estimate the size of the heliospheric bubble is one that Alan Cummings (PhD '73), a member of the professional staff, and I have been pursuing. We're looking at cosmic ray particles coming from the termination shock. These are called anomalous cosmic rays and originate as neutral atoms (hydrogen, helium, oxygen, neon, argon) from interstellar space flowing leisurely into the solar system. As they approach the sun, they become ionized and are carried back out to the termination shock by the solar wind at a million mph. Some of them will bounce back and forth across the shock for several years as their speed—initially only 0.1 percent of the speed of light—slowly increases with each bounce to as much as 10 percent of the speed of light. These anomalous cosmic ray particles then diffuse back inward toward the sun, some making it all the way to Earth.

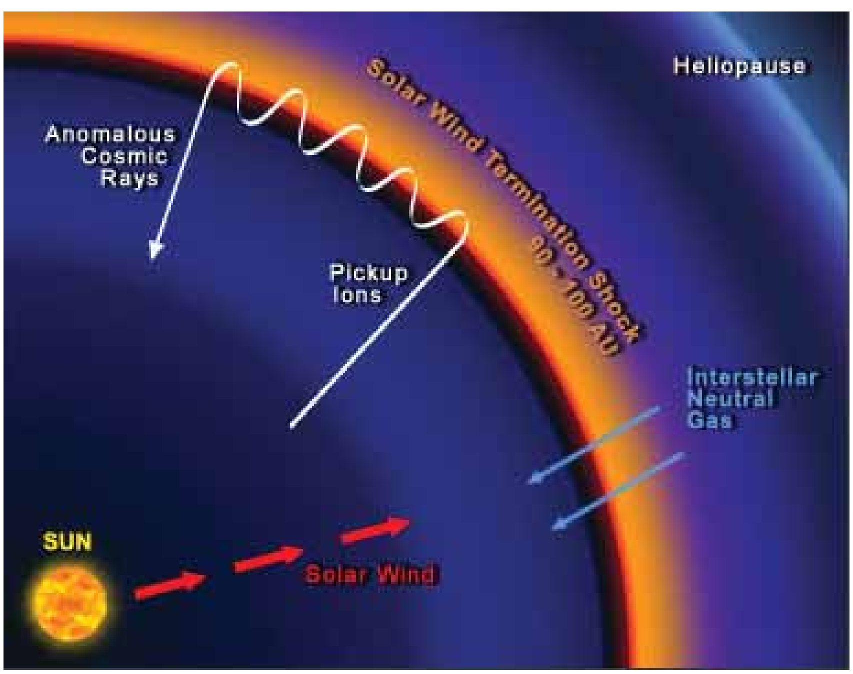
How does the acceleration of particles at the termination shock happen? It's essentially cosmic ping-pong. The solar wind, with imbedded magnetic irregularities, flows into the shock at a million mph, where it abruptly slows to 250,000 mph, causing the irregularities to slow as well. A cosmic ray particle, which is ionized, scatters off of the magnetic irregularities, bouncing back and forth like a ping-pong ball. As the ion bounces off the moving irregularities, it slowly gains speed. It may bounce back and forth across the shock for a year or two until it escapes from the region of the shock and diffuses back into the solar system.

Shock acceleration of a small fraction of the ions up to velocities approaching the speed of light is a fairly commonplace occurrence in the galaxy. In this case, we're using the ions accelerated at the termination shock to estimate how far it is to the shock. Because the anomalous cosmic rays originate at the shock, Voyager's cosmic ray detectors will observe an increasing intensity as it approaches the shock. By measuring the rate at which the intensity increases with increasing distance from the sun, we can extrapolate outward to determine how much farther away the shock is. We do that when solar activity is both at its minimum and its maximum.

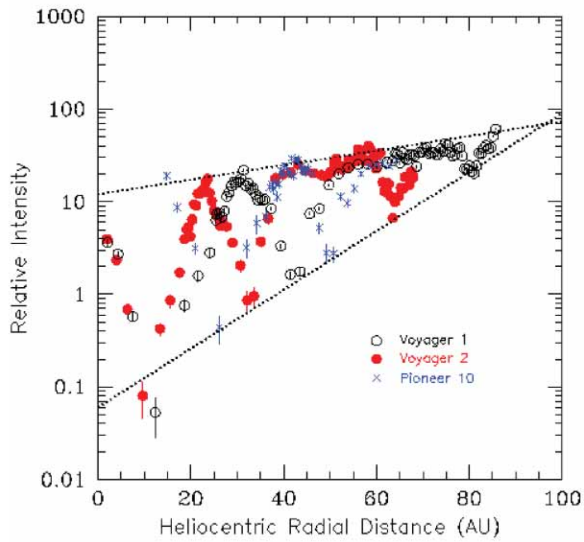
Cosmic rays are most effectively swept out when the sun is most active during its 11-year cycle. Even though the wind is slower at that time, it is more turbulent and more efficient at scattering cosmic ray particles and sweeping them outward. But when the sun is quiet, the wind is fast but much less turbulent, and the reduced scattering allows cosmic ray particles to diffuse inward more easily. So you would expect that during minimum solar activity, the cosmic ray flux intensity would not be much different closer to the sun than it is at their source. However, at maximum solar activity the intensity inside would be much lower than at the termination shock because cosmic rays are swept out more efficiently. That variation should happen with an 11-year cycle.

Voyager was launched in 1977, just at the end of a period of minimum solar activity, when there is a minimum of sweeping and the intensity is high. But by 1980, Voyager 1 and 2 were around 10 AU, and the intensity had decreased by a factor of 50 as the more turbulent solar wind swept most of the anomalous cosmic rays outward. A few years later, when Pioneer 10 (which was launched in 1972), Voyager 1, and Voyager 2 were at 43, 30, and 23 AU respectively, the sun was again quiet and the intensity was again high. At the next solar maximum in 1990, when the spacecraft were at 50, 43, and 33 AU, the intensity was again reduced, but higher than it was in 1980, when the spacecraft were farther from the shock. So, as expected, the intensity is higher closer to the shock.

We have a 30-year sequence of observations beginning with the launch of Pioneer 10. From the Voyager launches in 1977 until 1996, when Pioneer 10 no longer had enough power to measure the anomalous cosmic rays, we had spacecraft at three different locations to help us in extrapolating out to the shock. We can combine all these samples of space and time together in the plot at the top of the opposite page. If, instead of only three, we had a constellation of spacecraft spaced every AU between Earth and the shock at solar minimum, those spacecraft would have measured an intensity increase with radial distance as depicted by the top line, with the source of particles somewhere along the outward extension of the line. When the sun is very active, the set of spacecraft would have traced the much steeper



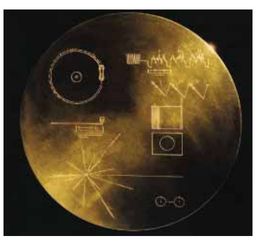
When anomalous cosmic rays—neutral atoms from interstellar space flowing into the solar system—get close to the sun, they become ionized and the solar wind carries them back to the termination shock. There they bounce back and forth across the shock, picking up enough speed for them to diffuse back in toward the sun. Measuring how their intensity changes with distance from the sun will help determine the distance to the termination shock.



Pioneer 10 and Voyagers 1 and 2 have been measuring the intensity flux of cosmic rays across 80 AU and 30 years, including three cycles of solar maximum and minimum activity. If, instead of three spacecraft, there were a whole fleet (one every AU), they would have traced the top line at solar minimum and the steeper bottom line at solar maximum, when the cosmic rays are more cleanly swept out. The lines meet at the source of the particles—the termination shock.

increase with distance as shown by the bottom line. And where these two lines meet is the source. This suggests that the source of the particles, the termination shock, is between 90 and 100 AU. And Voyager 1 is already beyond 88 AU and travels 10 AU every three years. So it might not be long before we get there.

But nature doesn't make it quite so easy. Remember that the heliosphere breathes over its 11-year cycle and is smallest when the sun is most active, because that's when the wind is slowest. Right now the termination shock is as close as it gets. The question is: how soon will it start moving farther away?

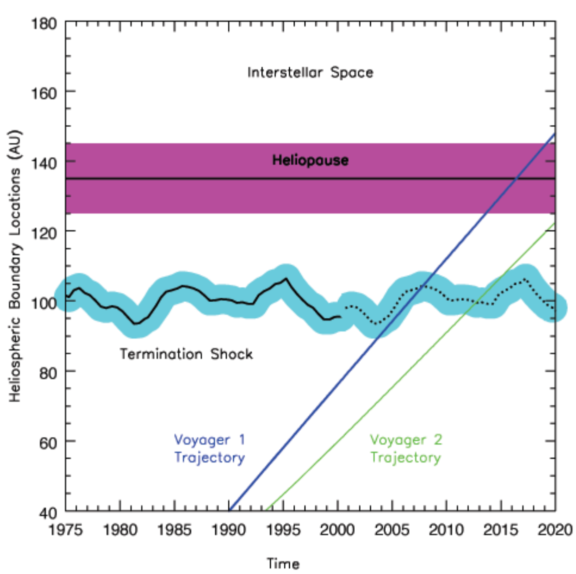


Voyager carries a disk of images and sounds of Earth into interstellar space.

Theoretical models based on the observed solar wind pressure data provide estimates of the movement of the shock as shown by the wavy black line in the figure below. The blue band around the line indicates the uncertainty in the estimate. As the heliosphere breathes in and out, the termination shock moves with it, ranging between 95 and 105 AU over the solar cycle. Because of the obvious differences among the solar cycles, it is not possible to predict exactly when the shock will start moving outward. As an illustration of what might happen, the dotted line shows the shock location if it were to mimic what happened 22 years earlier. This suggests that the shock is likely to be moving outward by sometime in 2005. If the shock is located near the lower edge of the blue band, Voyager 1 would encounter it before then, but if the shock is nearer the upper edge, it would take four more years to reach it, with Voyager 2 following five years later. So, we are in a race to reach the termination shock in the next two years before it starts moving outward, possibly faster than Voyager 1.

In the longer term, we're in another race—a race to reach the heliopause and enter interstellar space while Voyager still has enough electrical power to transmit data back to Earth. The heliopause is about 35 AU beyond the termination shock and is likely in the range shown by the magenta band in the figure, so it will be at least 10 years before Voyager 1 reaches the edge of interstellar space. Voyager is powered by plutonium 238, which has an 89-year half-life, so there should be enough electrical power to last until about 2020. The spacecraft is already 25 years old, so something else on the spacecraft may fail before that. But if nothing critical fails, it's possible that Voyager 1 could win the race and return the first observations from interstellar space.

That's where we are today in our continuing journey of discovery. Voyager 1 may encounter the termination shock in the next several years, followed five years later by Voyager 2. We will then have our first direct measure of the size of the heliosphere and how much farther it is to interstellar space. In 10 to 15 years, Voyager 1 will become our first interstellar probe, with Voyager 2 close behind. Both will begin an endless journey through interstellar space, carrying a message signifying that we have taken our first small step into our local neighborhood in the Milky Way. □



Because the heliosphere "breathes" in and out, the termination shock is a moving target. If Voyager 1 reaches the expanding termination shock (the bottom of the blue band in this model) by 2005, it could reach the heliopause (at the bottom of the magenta band) in another 10 years, with enough power left to radio back what it finds.

As project scientist for Voyager, Ed Stone oversaw all its scientific experiments, including one of his own: the cosmic ray experiment, which is now approaching the moment Stone has been waiting three decades for—when Voyager finally reaches the termination shock and sends back the first glimpse of the source of anomalous cosmic rays. Since his first NASA cosmic ray experiment in 1961, Stone has been principal investigator on nine NASA missions and co-investigator on five more. And he was also director of JPL from 1991 to 2001. Stone came to Caltech as a research fellow in 1964, after earning his PhD in physics from the University of Chicago. He has been professor since 1976 and the Morrisroe Professor of Physics since 1994, and was chairman of the Division of Physics, Mathematics and Astronomy from 1983 to 1988 and vice president for astronomical facilities from 1988 to 1990. This article was adapted from a November Watson Lecture, which can be viewed at http://atcaltech.caltech.edu/theater/.

Swiss Rolls and Oreo Cookies

by Sossina M. Haile

PICTURE CREDITS: 18, 22 – Bob Paz; 20 – Doug Cummings; 21, 23, 25 – UTC Fuel Cells; 21 – California Fuel Cell Partnership

"A simple chemical reaction between hydrogen and oxygen generates energy, which can be used to power a car producing only water, not exhaust fumes. With a new national commitment, our scientists and engineers will overcome obstacles to taking these cars from laboratory to showroom so that the first car driven by a child born today could be powered by hydrogen, and pollution-free. Join me in this important innovation to make our air significantly cleaner, and our country much less dependent on foreign sources of energy."
President George W. Bush, State of the Union Address, January 2003.

"The Stone Age didn't end because we ran out of stones." Anon.

We adapted this article from a Watson Lecture given in January.

Fuel cells are taking the country by storm. Even the president of the United States is talking about them. While automobile makers compete to make the first mass-market cars running on hydrogen or methanol, fuel-cell-driven power plants have already been installed in commercial buildings, hospitals, and homes. And research departments—mine included—are developing miniature versions that can fit in your pocket and be refueled with a shot of methanol or lighter fluid. Invented in 1839 by Sir William Grove, a Welsh lawyer and amateur physicist, fuel cells were more or less forgotten until NASA developed them for the space program in the 1960s. Why so much interest now?

World energy consumption is rising dramatically, and most of this energy is generated by the combustion of fossil fuels. Although there are enough reserves of oil, gas, and coal to last well into the next century, there's a lot of geopolitical uncertainty surrounding their supply (a major issue at the moment), and they're causing an environmental catastrophe. The global increase in atmospheric carbon dioxide levels is truly very worrying. These levels were stable until the industrial revolution in the early 1800s, then began to rise rapidly. It's quite clear that there's an anthropogenic reason for this, in part because of our fossil-fuel consumption, but also in part because of the way we've consumed the forests that would otherwise have absorbed the carbon dioxide. The consequence in terms of global warming is that there's been a small but significant increase in atmospheric temperatures since 1880. What impact will this have? People are still debating that question, but do we want to do this experiment? I'm fairly certain I don't. Oil consumption per capita in the industrialized world is four times the global average, so it's really incumbent on us in the developed world to help solve this problem.

Are fuel cells a possible solution? They're certainly very attractive, because they are much more efficient than combustion engines. Even if they run on fossil fuels, the amount of carbon dioxide produced per action taken (such as per mile traveled or per unit of electricity generated) is much smaller. Fuel-cell efficiencies can be as high as 60 percent, even 80–90 percent if combined with hot-water cogeneration, while combustion engines have much lower efficiencies, on the order of 10–30 percent. And fuel-cell efficiency is entirely independent of size, unlike combustion engines, which become more efficient the larger they get. So fuel cells are suitable for all sorts of applications, ranging from big stationary power plants to portable electronics. In terms of the environment, not only are carbon-dioxide emissions lower, but chemical reactions are very carefully controlled so that there are zero toxic emissions. Best of all, fuel cells are very well-suited to a hydrogen economy. Run on hydrogen, they are a truly zero-emission energy device.

How do they work? Hydrogen and oxygen put together will inherently react to form water, with the release of a lot of energy:

$$H_2 + {}^1/_2 O_2 \rightarrow H_2O + \text{energy.}$$

In the simple fuel cell shown on the following page, in which the fuel is hydrogen and the oxidant is oxygen, these two very reactive molecules are kept apart by an electrolyte, a material that lets only ions move through it. For the hydrogen to get to the oxygen, it has to turn into hydrogen ions, called protons (H^+). It does this by the reaction,

$$H_2 \rightarrow 2H^+ + 2e^-,$$

to give us two protons and two electrons. The protons travel through the electrolyte and react with the oxygen on the other side. There they pick up two electrons and give water as a by-product:

$${}^1/_2 O_2 + 2H^+ + 2e^- \rightarrow H_2O.$$

Electrons are produced on the hydrogen side (called the anode side, as in a battery) and consumed on

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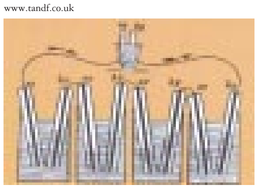
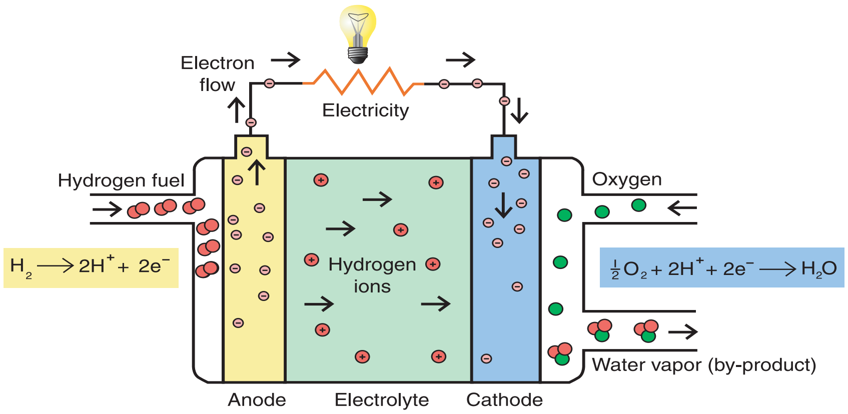


Above: Sir William Grove's 1839 gas battery, the first fuel cell, contrasts with Sossina Haile's miniature solid-acid fuel cell, aka "Oreo cookie," opposite.

How a simple fuel cell works.

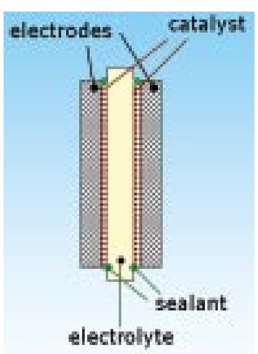


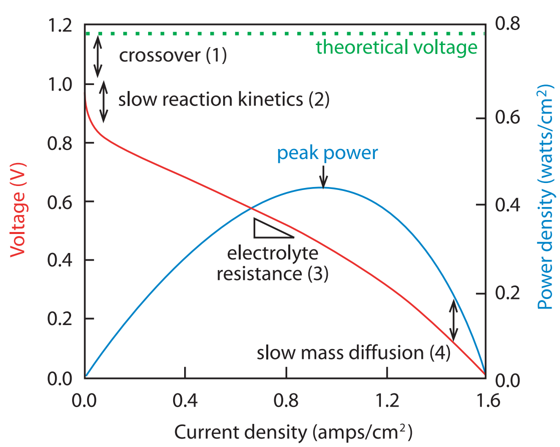
the oxygen side (the cathode side). When we connect the two sides with a wire, these electrons travel through the circuit and produce an electrical current that can power a device. (Without electrical contact between the anode and the cathode, no current flows and the hydrogen and oxygen remain unreacted.) This is similar to the way that a battery works, but fuel cells combine the best of batteries with the best of combustion engines—the best of batteries in that they have very well-controlled electrochemical reactions, so there aren't any dirty side-reactions that release pollutants, and the best of combustion engines in that they can be refueled. One thing to keep in mind is that a fuel cell is an energy *conversion* device, not an energy *source*. There are no toxic emissions, there's no pollution, but we still have to get the fuel from somewhere.

The electrolyte, often called the membrane, has to function as an efficient ion transporter, but it also has to block electrons—if any electrons were to move across the electrolyte instead of going through the circuit, there would be a drop in voltage between the anode and the cathode. The electrolyte also has to stop fuel and oxidant gases from coming into direct contact with one another, as any direct chemical reaction would reduce efficiency. At the electrodes, on the other hand, the ions, electrons, and gases all need to get together in order for a reaction to occur. So the electrodes are often composites that incorporate a catalyst, an ion conductor, an electron conductor, and something that will form pores at high temperatures so that gases can get to and from the electrolyte. The combination of electrolyte (or membrane) and two electrodes (which include the catalysts) is referred to as a membrane-electrode assembly. When this assembly is put inside a complete fuel-cell "engine," sealants are used to keep gases from leaking at the edges of the membrane.

A number of things can affect the efficiency of a fuel cell. In our simple hydrogen-oxygen cell, a theoretical voltage of 1.2 volts should be generated from the anode to the cathode in the open-circuit state, that is, when no device is attached. Once we put in some device that draws power, the voltage starts to go down, as shown in the graph on the left. This occurs for a number of reasons: (1) even in the open-circuit state, the fuel may be finding pores in the electrolyte and leaking across to the other side (crossover); (2) at small currents, the reaction kinetics at the anode and cathode may not be able to keep up with the rate at which electricity is being drawn; (3) the ions may meet resistance in the electrolyte as we try to step up the amount of current, and can't travel across it fast enough to keep up with the electrons; and (4) as we try to draw a lot of current, the gases can't diffuse in and out of the electrodes quickly enough. At this point the voltage really drops and eventually goes down to zero. The power that the fuel cell puts out is simply voltage times current, and it turns out that the cell doesn't generate the maximum amount of power at the point where it is working most efficiently. We use a voltage-current, or polarization, curve such as the one on the left to measure a fuel cell's performance. High-efficiency, high-power fuel cells have polarization curves in which the voltage stays high for very large currents.

There are five main types of fuel cells, differentiated essentially by the type of electrolyte used. Different electrolytes transport ions with different effectiveness as a function of temperature, so that each of these types operates in a different temperature range. PEM fuel cells (PEM stands both for polymer electrolyte membrane and proton exchange membrane) operate at low temperatures of 90–110°C. These are the ones now being developed





Above left: A membrane-electrode assembly. Above right: The performance of a fuel cell is measured by a voltage-current curve that plots the drop in voltage (red) as more and more current is drawn. The blue curve is the amount of power put out by the fuel cell at a given current (or voltage). The higher the point of peak power, the better the fuel cell.

Three alkali fuel cells like the one below left at the New Mexico Museum of Space History were used on *Apollo 13.* The "problem" began when an oxygen tank ruptured, damaging a second one and leaving two fuel cells unable to generate electricity. A leafy-green 200-kW phosphoric-acid fuel-cell plant generates power for the police station in Manhattan's Central Park, below right, and a snow-white quintet powers the main postal sorting facility in Anchorage, Alaska, right.

for use in cars, so there's a lot of excitement surrounding them. The type developed by NASA for the space program are alkali fuel cells that use a potassium-hydroxide electrolyte, and they operate at 100–250°C. They also supply the astronauts with drinking water, which is fine because the water generated is very pure. If you watched the movie *Apollo 13*, you may remember that fuel cells played a prominent role. A third type, phosphoric-acid fuel cells, are commercially quite well developed, and work at 150–220°C. Molten-carbonate fuel cells operate at a high 500–700°C, topped only by solid-oxide fuel cells at 700–1,000°C. The three types running at lower temperatures are fueled by hydrogen or possibly methanol, while the two high-temperature ones use hydrocarbons. At lower temperatures, reaction kinetics are slow, so one has to use very active and expensive catalysts based on platinum or other precious metals in the electrodes. Each type of electrolyte transports different ions, but in all cases the oxidant is oxygen (typically from air), and water is always a by-product. In some cases, carbon dioxide is also a by-product.

With all these different types of fuel cells, how do we pick the right one for a particular application? Temperature of operation is an important criterion. The low-temperature cells have the advantage of a very rapid start-up, so they're great as a portable source of power and can handle many on-off cycles. They're also easy to run as small-sized devices. But the low temperatures of operation mean they can only be run on hydrogen or methanol—the only fuels that react readily at or below the boiling point of water—and the catalysts in the electrodes are easily poisoned by impurities in the fuel stream. These impurities stick to the catalysts and stop the hydrogen or methanol from reaching them. Fuel cells running at higher temperatures have the advantage of being very fuel-flexible, because everything reacts more easily. The electrocatalysts also become very active when they're hotter, so the overall efficiency is significantly higher. Their disadvantage is a long start-up time. It takes quite a while for a fuel cell to get to 1,000°C, which isn't very useful in a portable power unit. (Imagine how long you'd have to wait to get your car started on a cold morning.) Not surprisingly, then, these high-temperature fuel cells are mainly used in stationary power systems where they can be left on all the time.

There are now many, many, demonstration power units and vehicles using fuel cells. Phosphoric-acid fuel-cell power plants generating 200 kilowatts of electricity have been used by the military in field operations since 1995, and many more currently provide power for buildings and homes—there's even an 11-megawatt power plant in Japan. And a stationary 100-kilowatt solid-oxide fuel cell put together by Siemens Westinghouse operated at a car plant in the Netherlands without measurable degradation for over 20,000 hours. So this is very much a demonstrated and commercially viable technology.

Both Toyota and Honda recently announced the first roadworthy PEM-based fuel-cell vehicles. UC Irvine and UC Davis are each leasing a Toyota FCHV (fuel-cell hybrid vehicle), and the city of Los Angeles is leasing a Honda FCX (fuel-cell experimental vehicle). There's a reason these first demonstration fuel-cell vehicles are in California—the state has a zero-emissions automotive standard that is really driving the technology. California also has a number of hydrogen-refueling stations, which other states don't have as yet (apart from

Toyota put a fuel cell into the popular Highlander, reasoning that Californians were unlikely to give up their Sport Utility Vehicles (SUVs).

one in Las Vegas, Nevada). The biggest barrier to the production of these cars for the mass market is cost, in the sense that the precious-metal catalysts are expensive, fabrication is costly, and the whole fuel-cell system is very complex. Another key issue is that there's a big uncertainty about the fuel infrastructure. How long will we continue to use gasoline? Is hydrogen going to be a reality, or will it be methanol? The White House is proposing a lot more money to build up a hydrogen refueling infrastructure, but administrations come and go, so will this really happen? Uncertainties like these are preventing car manufacturers from moving forward.

All fuel cells operate best on hydrogen, but even though it's the cleanest fuel possible, using it is a real challenge. In terms of watt hours per gram (Wh/g), a unit that measures how much inherent energy is in the fuel, hydrogen at 33 Wh/g is much better than diesel fuel (12.7 Wh/g), gasoline (12.9 Wh/g), and methanol (6.2 Wh/g), but because it's a gas it takes up a lot more room. This is why methanol, even though it has less energy per gram than hydrogen, is considered by some a much better fuel choice for a fuel-cell vehicle. But let's say we did want to use hydrogen. How can the large volume needed to fuel a car be packed into a portable container like a car fuel tank? The choices are to use materials that adsorb large amounts of hydrogen—some metals and some forms of carbon—or to put it into a high-pressure tank, which is the way hydrogen is carried on most demonstration fuel-cell vehicles. Many people won't be comfortable with having a tank containing hydrogen compressed at 5,000 pounds per square inch in their automobile but, more importantly, the tank itself will weigh a lot because the walls have to be thick to hold this much pressure. Typically, only 2–3 percent of the weight of a full tank will be hydrogen, and the numbers don't get much better for the adsorbant materials. For an automobile that does the equivalent of 20 miles per gallon of gasoline (at 0.6 miles per kilowatt hour of hydrogen) to have a 350-mile range, you need to carry 18 kilograms (40 pounds) of hydrogen. Add to that the weight of the tank itself, and you're at a hefty 720 kilograms (1,600 pounds). Most of the fuel-cell vehicles today have a smaller range, and rely on having a much higher efficiency rather than carrying a large amount of hydrogen around. The Honda FCX, for example, stores 3.75 kilograms of hydrogen in high-pressure tanks and has a range of 220 miles. Another challenge with using hydrogen is that because it is such a small molecule, it easily diffuses through many materials and is lost, just as the helium in a child's floating balloon eventually diffuses away.

The Honda FCX, left, is a zero-emission four-seater with a 220-mile range; this one was the pace car in the recent L.A. Marathon. It's pretty standard inside, above, but there's a sleek electric motor under the hood (the fuel cell sits under the middle of the body), and the fill pipe looks different, right.

And then there's the question of where to get the hydrogen from. It's possible to generate hydrogen by electrolysis:

$$\text{Electricity} + H_2O \rightarrow H_2 + {}^1/_2O_2,$$

which is almost the reverse of what happens in a fuel cell, but it's an expensive procedure. And surely it defeats the whole purpose of a fuel cell if you have to use electricity, probably generated from fossil fuels, to make the fuel for it—though it could perhaps make sense if solar, wind, or water power were used. The other way to get hydrogen, and the way it's done commercially today, is to react some sort of hydrocarbon fuel with water using a process called the reforming reaction, which produces carbon dioxide and hydrogen:

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2.$$

If the reaction does not go to completion, carbon monoxide is produced as well, and if the hydrocarbon fuel is not very clean, sulfur compounds

Most of the space inside one of those 200-kW power plants in Alaska on page 21 is taken up by auxiliary equipment. The blue-wrapped fuel-cell stack (unwrapped, left) is flanked on one side by fuel-processing, heat, and water-management systems, and on the other by power-conversion equipment.

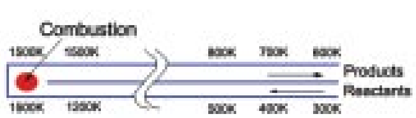
also are mixed with the hydrogen. Both carbon monoxide and sulfur compounds have to be removed before the fuel is introduced to the fuel cell.

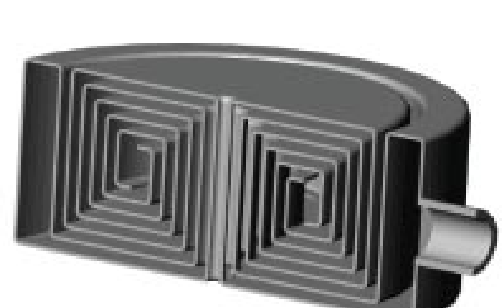
All of this leads to a great deal of complexity. The basic fuel cell is a really simple, beautiful little electrolyte; but then we add electrodes to extract the electricity, catalysts to get the reactions to occur, and sealants to prevent contact between the fuel and oxidant. To produce more power we join several cells together in series to make a stack, and then we put the stack into a large system with numerous components that reform the hydrocarbon fuel; deliver the hydrogen in the right way; ensure the temperature and humidity are right; get rid of unwanted gases; and convert the electricity from direct to alternating current. And so we end up with a large and very complicated system. Fuel cells are not quite equivalent to batteries in their simplicity and ease of use—at least not yet.

The limitations of today's fuel-cell materials place severe design constraints on the overall system. If we can improve the materials, and come up with novel integrated designs to make everything much less complex, we can have a major impact on what the system looks like. That's what my group at Caltech is concentrating on.

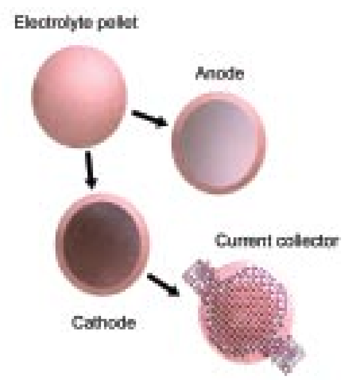
Let me tell you first about our project to put a single-chamber, single-oxide fuel cell inside a clever little heat exchanger to make a small, integrated micropower generator. We're collaborating on this DARPA-sponsored program with the Lawrence Berkeley National Laboratory, the University of Southern California (USC), and Northwestern University. Our goal is a portable box measuring about two centimeters per edge, and weighing as much as a golf ball, that can operate on propane or butane (the fuel used in Bic cigarette lighters) to give 200 milliwatts of power, enough to run a portable radio. Propane and butane have more energy per gram than methanol, are easier to handle than hydrogen, and have no storage difficulties.

How can we make a small box containing a stack of single-oxide fuel cells running at very high temperatures that is cool to the touch? That's where the heat exchanger comes in. In a linear counter-flow heat exchanger, the products leaving a combustion chamber exchange heat with the incoming reactants by flowing through a tube-like device so that the reactants are warmed up while the products are cooled down. If we roll up a linear heat exchanger into a coil, we get what we call a Swiss roll. We can even roll it up again and get a toroidal Swiss roll. This concept has been exploited by Paul Ronney at USC to make all sorts of microcombustors. It's quite easy to maintain a





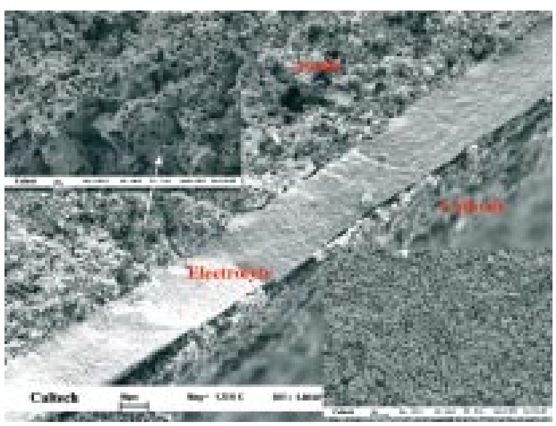
By rolling up a linear heat exchanger, we get a Swiss roll (center), which could be further rolled into a toroid, like the one on the right designed by Paul Ronney at USC.



Above left: To make one of our single-chamber, solid-oxide fuel cells, a dime-sized electrolyte pellet, 500 microns thick, has anode and cathode materials deposited on each face before silver current collectors are attached. We're going to squeeze a stack of these fuel cells into the center of one of Robert Shepherd's Swiss rolls, above right. In the scanning electron micrograph on the right you can see that we've achieved an electrolyte that's only 20–30 microns thick. We did this by using a mechanically strong anode material and depositing the electrolyte and cathode materials onto it.

temperature of 500°C in the center of one of these while leaving the exterior close to room temperature. This is exactly what we need for operating a micro single-oxide fuel cell. A catalytic after-burner next to the fuel cell to burn off any unused fuel will also make sure the temperature in the center remains what we'd like it to be.

Now how about that single-chamber, single-oxide fuel cell? You'll remember that in a conventional fuel cell, fuel and oxidant have to be kept separate. But by using very well-designed catalysts at the electrodes, it has now become possible for them to be mixed together in the same chamber, which makes the design much less complex and eliminates the need for sealants to separate fuel and oxidant.



Sealants are very problematic in fuel cells that get turned on and off frequently, because they can't handle the changes in thermal expansion and contraction, and tend to crack. My group can't take the credit for the single-chamber innovation, but we're working on adapting it for our integrated micropower generator. The way it works is that at the anode, the fuel (in this example, methane) reacts with oxygen to give carbon monoxide and hydrogen, a process known as partial oxidation:

$$CH_4 + {}^1/_2O_2 \rightarrow CO + 2H_2.$$

A high concentration of carbon monoxide and hydrogen builds up at the anode side and, in principal, none builds up at the cathode side. The anode can continue to do its conventional electrochemical reactions that generate electrons,

$$H_2 + O^{2-} \rightarrow H_2O + 2e^- \quad \text{and}$$

$$CO + O^{2-} \rightarrow CO_2 + 2e^-,$$

while at the cathode, through the conventional electrochemical reduction reaction, electrons are consumed:

$${}^1/_2O_2 + 2e^- \rightarrow O^{2-}.$$

The fuel and oxidant can only be together in the same chamber as long as the temperature is low enough to prevent any gas-phase reaction. Hydrogen and oxygen as gases react explosively, so we have to be careful that we don't cause the experiment to explode by letting it get too hot. We also have to make sure all the reactions occur at the surface of the catalyst.

Our development effort is to come up with anodes that catalyze partial oxidation and electro-oxidation, and cathodes that catalyze electrochemical reduction but don't allow any oxidation reactions to occur. It's quite a challenge. We're also trying to make the electrolyte as thin as possible, between 5 and 50 microns, to minimize the resistance losses I mentioned earlier. The paper this is printed on is about 75 microns thick, so our membranes will be thinner. They will be made of a ceramic material similar to the electrolyte used in a conventional single-oxide fuel cell, and will be supported on one side by a thick but porous anode to provide mechanical strength and let the gases in and out, and on the other side by a very thin and porous cathode. In terms of performance, the fuel cell needs to provide about 75 milliwatts per square centimeter in order for us to meet our target of 200 milliwatts for the overall device. It will have an operational temperature of about 500°C.

So far we've optimized the composition of the various components, the fabrication routes, and the gas flow and composition, and our fuel cell can reproducibly reach close to the target power output, so we're happy with that. In terms of making a functional device, we also have to get this fuel cell to work inside the Swiss roll. As you can imagine, we've had a bit of a tough time getting the wires in and out without shorting the device. Once we learn how to properly wire things up, we plan on using the beautiful Swiss-roll structures being made by Robert Shepherd, a graduate student working with Professor Jennifer Lewis at the University of Illinois, Urbana-Champaign. All in all, it won't be very long before we have a micro single-oxide fuel cell for portable power.

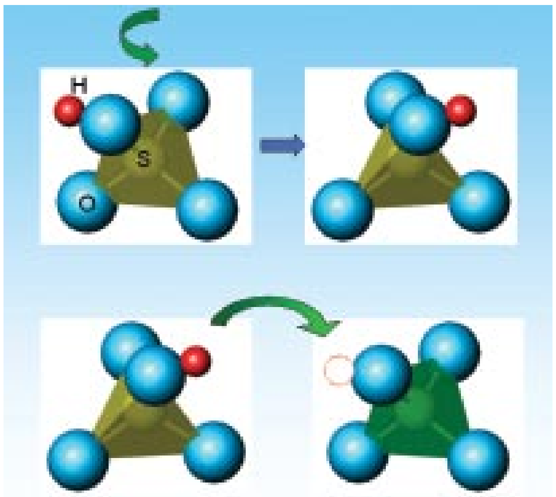
My research group is also working on alternative electrolytes for low-temperature PEM fuel cells. The state-of-the-art membrane polymers used in these fuel cells, such as Nafion from DuPont, work because they're full of water regions. Water molecules can pass through the electrolyte by moving from one water region to another, and protons hitch a ride by forming what we call hydronium ions:

$$H_2O + H^+ \rightarrow H_3O^+.$$

Once the hydronium ions get over to the cathode side, the protons jump off:

$$H_3O^+ \rightarrow H_2O + H^+.$$

The advantages of this material are that it has very high conductivity, flexibility, and strength. But water has to be recycled from the cathode back to the anode in such a way that the cathode isn't



When solid acids are warmed, their bisulfate groups reorient, changing the spatial position of the red hydrogen atom so that it gets the chance to jump over to the next sulfate group.

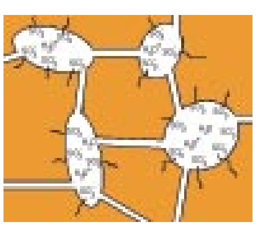
flooded or the anode dried out, which really adds to the overall complexity. Moreover, the fuel cell has to be operated at temperatures below the boiling point of water so that it doesn't dry out, which means you can't take advantage of the fact that catalysts are more effective at slightly higher temperatures. There's also a higher likelihood the catalysts will be poisoned by impurities in the fuel stream at this low temperature: poisons like carbon monoxide desorb quite easily if the temperature is just a little bit higher. Another disadvantage of a polymer with a lot of water in it is that methanol can diffuse right through, which is a very serious problem if you want to use methanol instead of hydrogen as the fuel.

For the above reasons, and also because it would be advantageous for automotive applications, we'd like to operate at slightly higher temperatures. We're looking at inorganic proton conductors called solid acids, which are chemical intermediates between normal salts and normal acids. If we take a normal acid such as sulfuric acid and react it with a normal salt such as cesium sulfate, we end up with cesium hydrogen sulfate (cesium bisulfate):

$$^1/_2Cs_2SO_4 + {}^1/_2H_2SO_4 \rightarrow CsHSO_4.$$

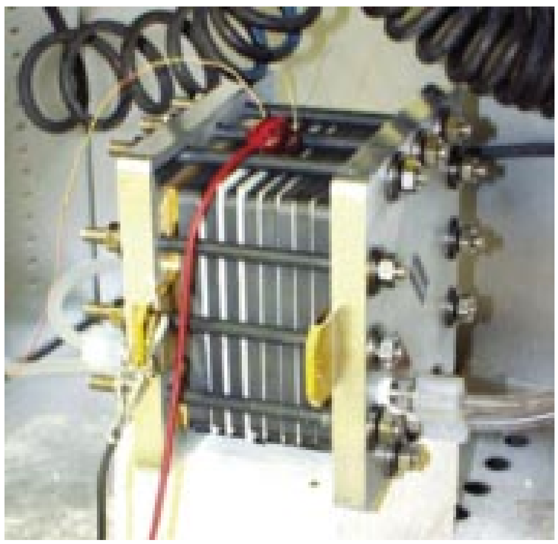
This is our prototype solid-acid compound, one that has protons in the structure even though it's a solid. Physically, it's similar to a salt, and at low temperatures it has a very normal structure without any disorder in it. But at warm temperatures it undergoes a structural disordering that causes the conductivity to increase dramatically. The advantages of these solid acids are that they transport "bare" protons (not ones hitching a ride on water molecules), they're inherently impermeable if you can manufacture them without any pores, and their conductivity is humidity insensitive. By operating at warm temperatures we don't have to make sure that absolutely no carbon monoxide is left in our hydrogen fuel, which simplifies the system tremendously and makes the fuel cell much less costly. One disadvantage of solid acids is that they're brittle. Another is that they're water soluble—and as water is a by-product of the fuel-cell reaction, we've had to devise a way to get around this.

I find the proton transport mechanism in these solid acids quite fascinating. The bisulfate (HSO_4^-) group forms a tetrahedron with an oxygen atom at each corner and a hydrogen atom sitting on one of the oxygens. At room temperature, all the sulfate groups have a fixed orientation. When we raise the temperature, disorder sets in and the sulfate groups reorient, changing the positions of the hydrogen atoms as they do so. The time frame for this reorientation is about 10^{-11} seconds. Every once in a while, a proton from one sulfate group transfers over to the next. This transfer is on the order of 10^{-9} seconds. Essentially, these sulfate groups rotate almost freely—and every 100 reorientations or so, they're in exactly the right position for a proton transfer to happen. As the material goes through this transition, there's a sudden increase in conductivity of several orders of magnitude. Conductivity values for the acid salts are comparable to the conductivity of Nafion and other electrolyte polymers, but at slightly higher temperatures. A number of different solid-acid compounds with such behavior have been discovered, quite a few of which have come out of our laboratory. We're searching for others, and I'll tell you more about that further on.



Polymer electrolyte membranes (PEMs) like Nafion, the cellophane-like material in the photo, have sulfonic acid side-groups that form interconnected watery regions within a Teflon-like matrix, through which protons can move from anode to cathode as hydronium ions (H_3O^+). The membrane-electrode assembly in the photo is the working heart of all PEM-based fuel-cell stacks.

The potential of fuel-cell technologies for reducing our reliance on fossil fuels, and the environmental damage of our energy consumption, is tremendous.



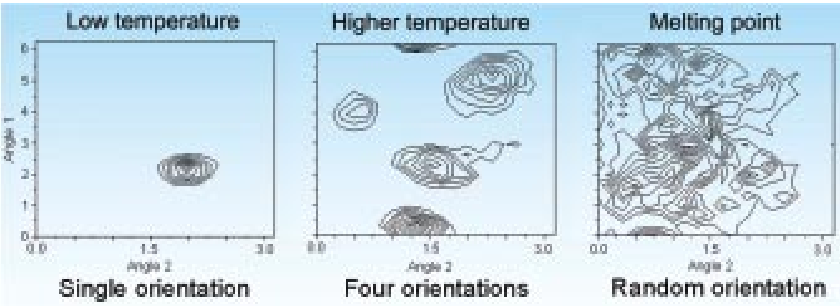
The little fuel cell that could: to show that our "Oreo cookies" (above) generate electricity, we put them into a stack (right) wired up to an LED display (bottom). It worked!

We've made a fuel cell using cesium hydrogen sulfate—the white central layer in the close-up of the pellet on the left. The current collector, which is graphite paper, is the dark outer part. In between are the electrocatalysts, but they're too thin to see. My students sometimes like to call these fuel cells Oreo cookies, hoping they'll get sponsorship from Nabisco (which hasn't happened quite yet). Although these electrolytes are water soluble, we can get them to work if the cell is operated above 100°C. We've achieved a very high open-circuit voltage with this fuel cell—much better than with PEM fuel cells. But overall, the power we're getting is quite low, only 10 to 15 milliwatts per square centimeter, so we still have to make our electrolytes much thinner (the one in the photo is 1,400 microns thick, and we'd like to get down to 20 microns) and find better ways to put the catalysts on.

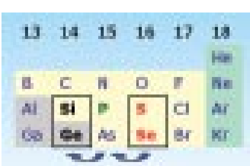
Nevertheless, the proof of principle is there, so we've gone ahead and made a stack out of these cells. We purchased a commercial stack, put our own membranes inside, and connected them to an LED to demonstrate that the cells were generating a current. We also ran the stack in direct-methanol mode, and again got a substantial open-circuit voltage compared to PEM fuel cells running on this fuel. Solid-acid electrolytes don't have any problems with methanol permeability, so we can use quite a high methanol concentration, which is one of the reasons we can achieve such a good voltage.

Now for the fly in the ointment. After we operated our fuel cell for some time, the performance started to degrade. It turned out that the cesium hydrogen sulfate electrolyte was being reduced by hydrogen to produce hydrogen sulfide, a terrific poison not only for human beings but also for the platinum catalyst. So now we're engaged in a search for solid acids that are stable in hydrogen. Many of the solid-acid compounds known to have a high conductivity when heated are sulfates and selenates, but this phenomenon has also recently been found in phosphates and arsenates. Phosphorus and arsenic are one group to the left of sulfur and selenium in the periodic table. If we go one more group to the left, we find silicon and germanium. Do silicates and germanates also have high conductivity? We're looking at the many possible chemical analogs of cesium hydrogen sulfate, such as barium hydrogen phosphate, strontium dihydrogen germanate, lanthanum hydrogen silicate, and so on, to see if their conductivity also rises when heated. These alternatives are all stable in hydrogen, which is what we're looking for. Moreover, many are water insoluble, which is great for the application, but makes them much more challenging to synthesize.

To guide our synthesis efforts, we're doing computational studies in collaboration with Bill Goddard, the Ferkel Professor of Chemistry, Materials Science, and Applied Physics, that allow us to predict the properties in advance before we go through the very difficult exercise of synthesizing



Using theoretical calculations, we can accurately predict the way a single sulfur-oxygen bond of cesium hydrogen sulfate reorients when the temperature is raised.



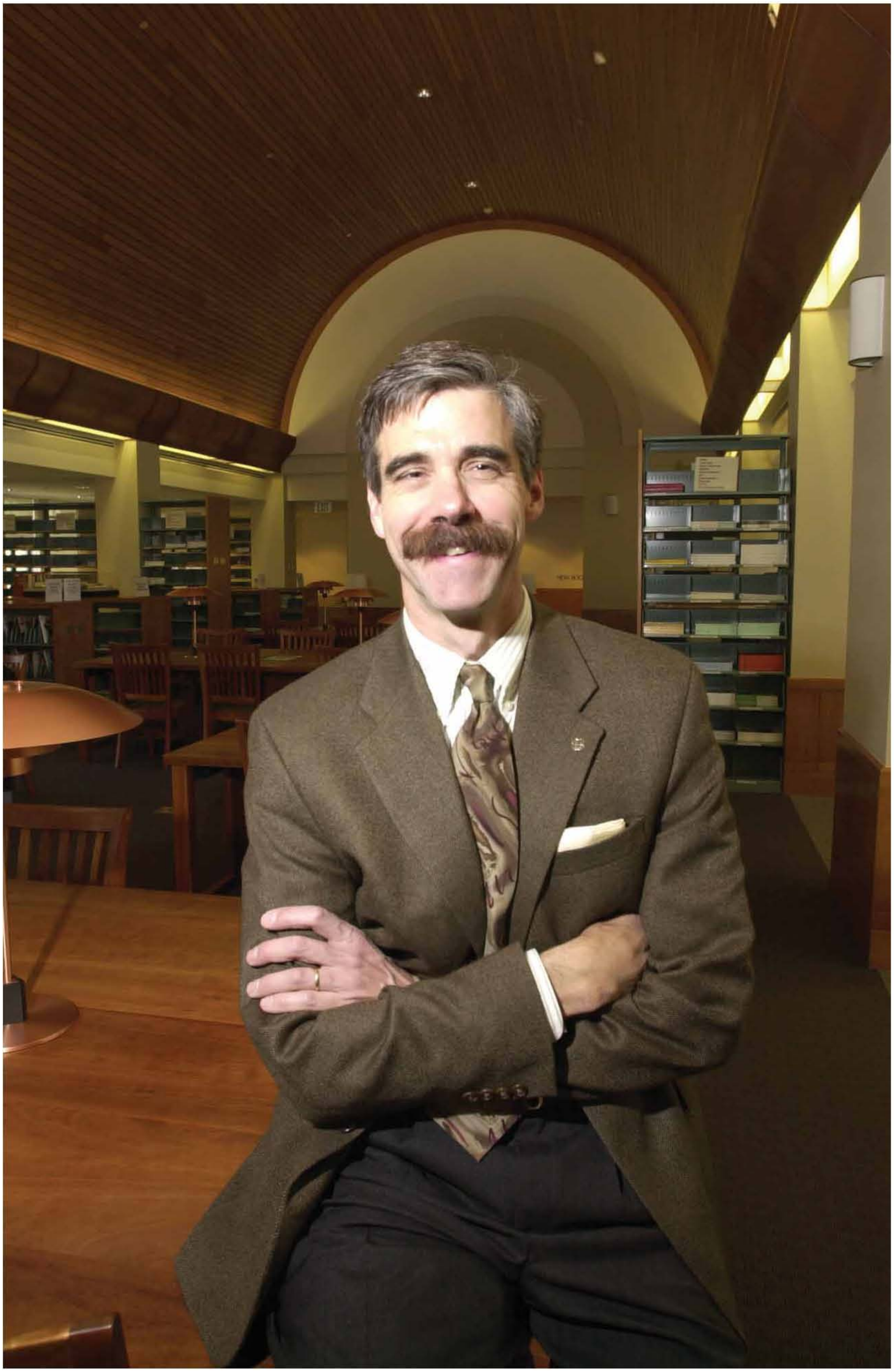
This area of the periodic table will hopefully yield more candidates for solid-acid electrolytes.

them. We started our computation exercise with cesium hydrogen sulfate, to show that we could do it. Basically, we were trying to work out theoretically—with no experimental input—how the positions of the cesium, hydrogen, sulfur, and oxygen atoms in the solid acid change as we change the temperature. We put these atoms in an imaginary box, worked out the forces acting between them using quantum-chemistry calculations, and simulated the way they would interact with one another. The diagram above shows the computed orientation of a single sulfur-oxygen bond, relative to the edge of the box, at different temperatures. At low temperature, the sulfur-oxygen bond always points in the same direction, meaning the sulfate group has only one orientation. At a higher temperature, there are four different directions, meaning four different orientations, which is exactly what we see experimentally. This is a terrific result because it means we can correctly predict the disordered, high-proton-conductivity state, and we now have a handle on determining which materials are going to give us this behavior. We hope to answer a lot of scientific questions: What types of compounds exhibit this transition to a disordered state? Do silicates and germanates have it? Can it be predicted? Can we manipulate the transition temperature and even the conductivity? And ultimately, we're heading toward a water-insoluble, stable electrolyte that will revolutionize portable, low-temperature fuel cells.

I'm hopeful that the novel power devices we're currently developing will be widely adopted in the not-so-distant future. The potential of fuel-cell technologies for reducing our reliance on fossil fuels, and the environmental damage of our energy consumption, is tremendous. It is essential that our work succeed: we have a moral obligation to deliver a sustainable world to the next generation and beyond. □

Associate Professor of Materials Science and Chemical Engineering Sossina Haile gained her BS (1986) and PhD (1992) from MIT, and her MS (1988) from UC Berkeley. A 1991 Fulbright fellowship took her to the Max Planck Institute for Solid State Research in Stuttgart, Germany, where she continued as a post-doctoral student and Humboldt Research Fellow until a faculty position at the University of Washington brought her back across the Atlantic in 1993. She moved to Caltech in 1996. Although still at an early stage in her career, her research has already garnered prestigious awards such as the National Young Investigator Award of the National Science Foundation, the Robert Lansing Hardy Award of the Minerals, Metals, and Materials Society, the American Ceramic Society's Robert L. Coble Award for Young Scholars, and the J. B. Wagner Award of the Electrochemical Society's High Temperature Materials Division. The Watson Lecture can be viewed on http://atcaltech.caltech.edu/theater/.

Will the fuel cells being developed at Caltech today be everyday objects for Alemayouh Haile Snyder by the time he drives his first car (hydrogen-powered, of course)?



The Chief Technologist's Mechanical Advantage

by Douglas L. Smith

Erik Antonsson, JPL's new chief technologist, in the reading room of the Sherman Fairchild Library of Engineering and Applied Science, which features wireless networking and e-publishing technology.

Erik Antonsson is a builder of bridges. Not literally—he's a mechanical engineer, not a civil one. He's a hands-on, axles-and-wheels kind of guy. His Caltech office has an entire bookshelf devoted to gears, bearings, and mysterious yet intriguing fittings, all within easy reach of the visitor's chair; on the next shelf up, some actual books jockey for position with a dozen electric motors of various sizes, a miniature purple Chrysler Prowler, and a tiny Sojourner rover. Yet his chief research interest is theoretical: engineering design, which is the study of the *process* of designing things, be they bridges, electric shavers, or spacecraft. And now that he's chief technologist at the Jet Propulsion Lab, which Caltech runs for NASA, and which is the home of America's missions to the far corners of the solar system, he builds bridges between really cool but possibly far-out ideas and the funds to incubate them.

Antonsson's father was an aerospace engineer for General Electric. "He tried very hard to keep me from being an engineer," Antonsson recalls, "because he thought that the profession was too uncertain—this was during all the ups and downs in the late '60s and early '70s—but there was no question that I was wired up to be an engineer." Engineers hang from every branch of his family tree: one grandfather and an uncle were mechanical engineers; his other grandfather, who never attended college, was a machinist and a tool-and-die maker. "Had he had the opportunity to get a formal education, he would have undoubtedly pursued engineering. He was tinkering and inventing all the time. And—this tells you what the dinner-table conversations are like when the family gets together—my older sister married a mechanical engineer. It's in the blood, I'm afraid. I recall taking a clock apart once when everyone, including my parents, were utterly convinced that I was way too young to have done so. I remember getting punished for that, which taught me that if I were going to take things apart, which I knew that constitutionally I couldn't resist doing, I had to make sure that I could put them back together." At 14, he spent $25 on a car, fixed it, sold it, and used the proceeds to buy the next, an "affliction" that lingers today; he's also worked as a production machinist, plumber, mason, carpenter, and electrician. "So it's sort of laughable that my father thought he could convince me with mere words that I *shouldn't* be a mechanical engineer."

Not that a convergence of the stars and his genetics set Antonsson on a beeline for Caltech and JPL—far from it. He attended McGill University his freshman and sophomore years. He loved Montreal but McGill wasn't his "cup of tea," and his grades showed it. "So I applied to transfer but, being the headstrong young man that I was, to only one school. I figured that if I couldn't get in where I really wanted to be, I'd go drive a truck." That one school was Cornell, which had interviewed and accepted him two years earlier. He must have made a good impression, as they welcomed him back, and Antonsson remains grateful to this day. "I don't think it's unreasonable to trace my being at Caltech—and the opportunities I've had as a result of that—back to this admissions officer who, for whatever reason, thought there was some merit to readmitting me as a transfer student" despite Antonsson's lackluster transcript.

Cornell turned him around. He took a course in biomechanics—the study of how bones and muscles move, which one might call the pinnacle of mechanical engineering—from Donald Bartel, "who I still maintain an infrequent correspondence with." Bartel was doing pioneering work with artificial hip joints, the first full hip-replacement surgery having been done a few years earlier. "When I came back for my senior year, as I got to the mechanical engineering building, the department secretary stopped me and said, 'Oh, Professor Bartel wants to see you.' And my heart sank. I thought, 'Oh no, he's going to take back that A

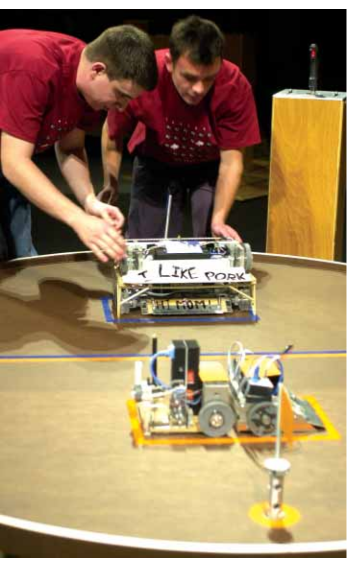
Above: Antonsson makes great strides toward his PhD. The round things strapped to his body are plates bearing LEDs, whose travels are recorded by the two infrared cameras on the adjustable rails in the background. (In a real experiment, the LEDs would be facing the cameras.)
Right: The apparatus was also worn by more graceful volunteers, including this member of the Joffrey Ballet.

that he now realizes is a mistake.'" Instead, Bartel offered him a job. "So I got involved in doing biomechanics research with dogs at the vet school, and enjoyed it greatly." Antonsson graduated with a BS in mechanical engineering, with distinction, in 1976, and Bartel "encouraged me to apply to graduate school, which I didn't want to do. There was *nothing* I wanted more than to get *out* of school. But I *really* liked doing research, so I applied to several schools, including MIT. MIT offered me a research assistantship, and how could I say no to that?"

Antonsson earned his MS and PhD degrees with Robert Mann, the founder of MIT's Newman Lab for Biomechanics and Human Rehabilitation, developing a better way to measure human joint motions. The system used two infrared cameras to track some five dozen small LEDs attached to the patient's body in precise clusters in strategic locations. A computer flicked each LED on and off, one by one, some 150 times per second, and calculated its 3-D position to within one millimeter and the orientation of the cluster to within one degree—an "unparalleled" precision at the time. Three LED clusters attached to a limb sufficed to track its motion unambiguously, and the system had enough clusters to scan the whole body. "The original purpose was to measure walking motions with enough speed and precision to be able to calculate the net forces and torques at each joint" for a study of osteoarthritis, says Antonsson. However, because of the system's generality, "it has been used to measure the motions of athletes—luge starts, baseball pitching, golf and tennis swings, etc.—and the pre- and postoperative gaits of children with cerebral palsy. I also spent a very interesting day with several members of the Joffrey Ballet, and at one point we collaborated with a researcher at the Salk Institute investigating hand motion in American Sign Language." After graduating in 1982, he adapted the system for clinical use at Massachusetts General Hospital while a postdoc at Harvard Medical School, working with Dr. Andrew Hodge. "He did all the clinical and hospital-political work; I did the technical work." Hanging out in hospitals had its pluses: while a grad student, he met Barbara Ann Bettick, a pediatric ICU nurse at Children's Hospital, another Harvard teaching affiliate. They married in 1985.

Antonsson started as an assistant professor of mechanical engineering at the University of Utah in January 1983. But first, he shopped around. "I was interviewed by people from several universities, including a conversation with Fred Culick [Caltech's Hayman Professor of Mechanical Engineering and professor of jet propulsion]. And I turned him down flat. I told him I'd never live in Los Angeles, so I didn't need to waste his time or mine with further discussion. I grew up in rural upstate New York, and Los Angeles just seemed too big, too dirty, just all this urban miasma. So I went off to the University of Utah—there's a pattern emerging here, as you'll see—which I shortly discovered also wasn't my cup of tea." Fortunately, Culick wasn't easily put off. In a time-honored tradition dating back to when Robert Millikan was luring Arthur Noyes from That Other Institute of Technology, "Culick made it his business to come to the University of Utah—gave a great seminar on his work on the Wright Flyer—and made a point of meeting with me. He said, 'Look, why don't you come down to Caltech and give a seminar?' And I said, 'Fred, I'd be happy to. I should know more about Caltech. But I'll tell you right now I'll never live in Los Angeles.' So I came out to Caltech for a day or so, and I was absolutely floored by the experience. I got back to Salt Lake, and called Fred up and said, 'You know, I really need to rethink this.'" Antonsson left the University of Utah that December, having been there exactly a year.

He joined Caltech as an assistant professor of mechanical engineering in September 1984, after a nine-month detour at Massachusetts General to put the finishing touches on what is now called the Biomotion Laboratory. Today, nearly 20 years later, it's still going strong. "We are one of the



Above: Salomen "Sam" Trujillo (center) of the Invaders is still in the game in the 2002 ME 72 competition, but partner Tyler Kakuda (right) watches helplessly as his device and the team flag are sumo-wrestled out of the ring by Brian Helfinger of the aptly named Atomic Wedgies in the final round. Teaching Assistant (and Antonsson grad student) Fabien Nicaise looks on.

Left: You can stack 'em or park 'em side by side, but everything must fit in your team's starting box and the amount of time you have to set 'em up is strictly limited—a rule that's been in force since the very first competition.

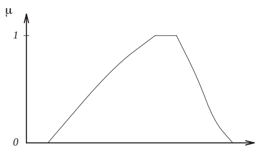
Below: In that first contest back in 1985, Antonsson (far right) watches Chris Schofield (BS '87) claim the championship.

more successful motion-analysis labs around," says Dr. David Krebs, its current director. "We use the same hardware Erik set up, but I suspect even he'd be amazed at the beneficent effect that cheap computers, motivated and smart engineers and scientists—and, yes, doctors!—have had!" They did their best to hang on to him, making him technical director of the lab, an assistant in bioengineering in the hospital's orthopedic surgery department, and an assistant professor of orthopedics at Harvard Medical School.

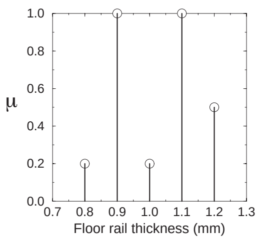
At Caltech, Antonsson has inspired undergraduates the way Professor Bartel inspired him. He initiated the hugely popular Engineering Design Laboratory, better known as the ME 72 contest, based on a course he'd TA'ed at MIT taught by the legendary Woodie Flowers, another Mann protégé. (The MIT catalog listed it as course 2.70, mechanical engineering being Course 2, so the Caltech course number is an homage.) "I have considerably extended the original; however, the underlying philosophy and broad outline of the course are straight from Woodie." ME 72 students are given a set of specifications and identical "bags of junk" from which to build contraptions to go head-to-head with their classmates' machines in a task that changes each year. Classroom topics include such things as "Gears, Belts, Chains, Clutches, and Brakes," and many long hours are spent in the machine shop on the prototypes that must be submitted at various "milestones." The course is a real-world exercise in designing a device from scratch with limited resources, and building, debugging, and sometimes entirely rethinking it under tight deadlines—useful experience for budding NASA engineers and future toaster designers alike.

The payoff is very public: the first contest, featuring rubber-band-powered scooters that raced down a slotted track to the far end of a 16-foot table and back, drew a crowd of 50. Corporate sponsorship has led to much higher-quality "junk" since then, and at last year's competition 894 onlookers watched pairs of radio-controlled, battery-powered rovers work cooperatively to plant their flag in a socket on the opposing team's side of the arena. ME 72 is now the most popular spectator event on campus—it packs Beckman Auditorium, the glee clubs sing the national anthem beforehand, and local (and occasionally national) television news crews turn out for it. In such a setting, showmanship counts, and Antonsson is fond of reminding his contestants, "If you can't win, lose with style." So does finesse—this isn't *BattleBots*, and devices designed to destroy or maim the opposition are not permitted. Fittingly, ME 72 won Antonsson the Feynman Prize for Excellence in Teaching in 1995.

ME 72 students face a fresh design challenge each year, and must choose their strategies before they can plunge into construction. Will knobby wheels or tank treads be better for climbing?



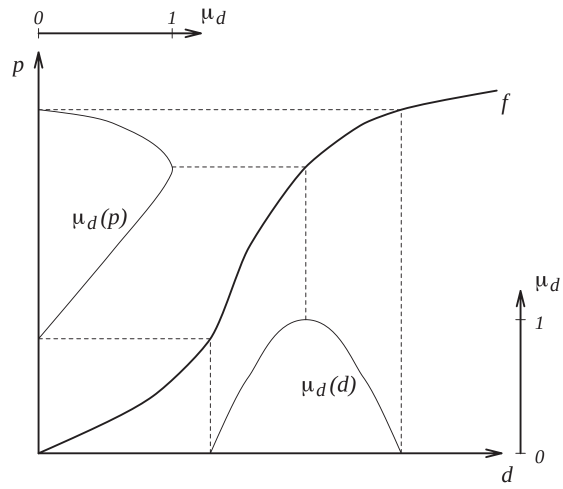
Antonsson, Imprecision in Engineering Design, *Proceedings of IDEA '97*



Scott and Antonsson, *Proceedings of DETC '98* © ASME 1998

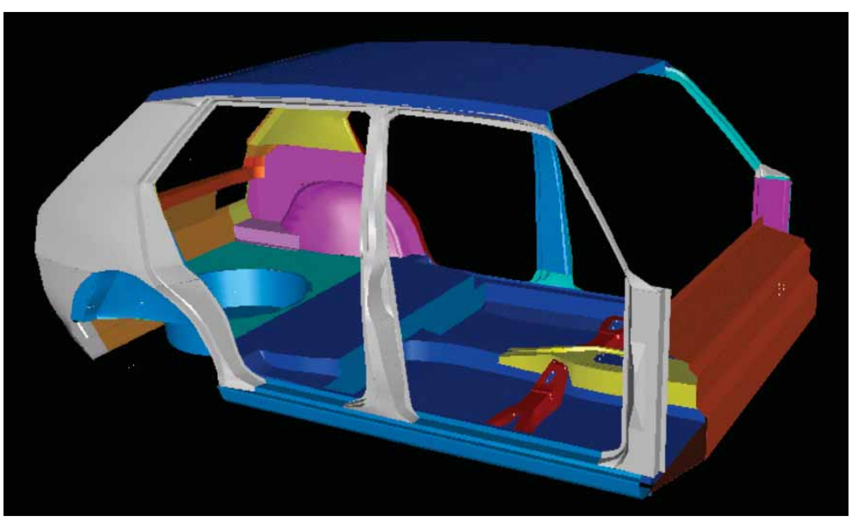
How do you explain "five-ish" to a computer? In the Method of Imprecision, you plot a design variable against your preference (μ) for each of its possible values, as shown at top left. The region where μ = 1 tells the computer, "this is what I want," while any value over zero says, "I can live with this." The variable doesn't need to be continuous, as in the plot of sheet metal thicknesses at bottom left, where μ reflects how easy each thickness is to come by. You find the optimum values by plotting a design preference (*d*) against a performance preference (*p*), at right, using a method proposed in the 1960s by Lotfi Zadeh, who invented fuzzy logic—at least in the mathematical sense. In reality, each *p* usually depends on many *d*s and the curve *f* is a multidimensional surface.

Antonsson, Imprecision in Engineering Design, *Proceedings of IDEA '97*



Should I build a catapult-launched grappler to sail over a competitor, or a wedge-shaped battering ram to flip my opponent's device on its back? It's not obvious what the best approach is, as Antonsson takes pains to create problems with many promising solutions. This ties in with the theme of his own research: developing ways to design things more efficiently. Even if you know what you want to build, you have to make a lot of decisions up front with very little to go on. Yet these decisions are generally the ones with the most expensive consequences if you guess wrong. And you *will* have to guess, because most computer-assisted design and rendering packages require precise inputs: when the system prompts you to input the length of a strut in inches, for example, typing "5-ish" into the dialog box won't fly. But, as Antonsson's group has discovered, relatively small changes in these early choices can have a significant effect on how the design performs. That's because the devil is in the trade-offs: frame thickness vs. stiffness, stiffness versus weight, weight versus fuel consumption, and so on.

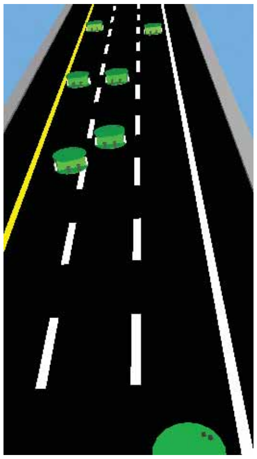
A computer model of the body members of a 1980 Volkwagen Rabbit, made by Michael Scott (MS '94, PhD '99), Zee Khoo (BS '98), and Juan Nuño (BS '99). Scott plugged in various thicknesses for the assorted pillars and panels to see how the body's stiffness changed, and evaluated the results with the Method of Imprecision.



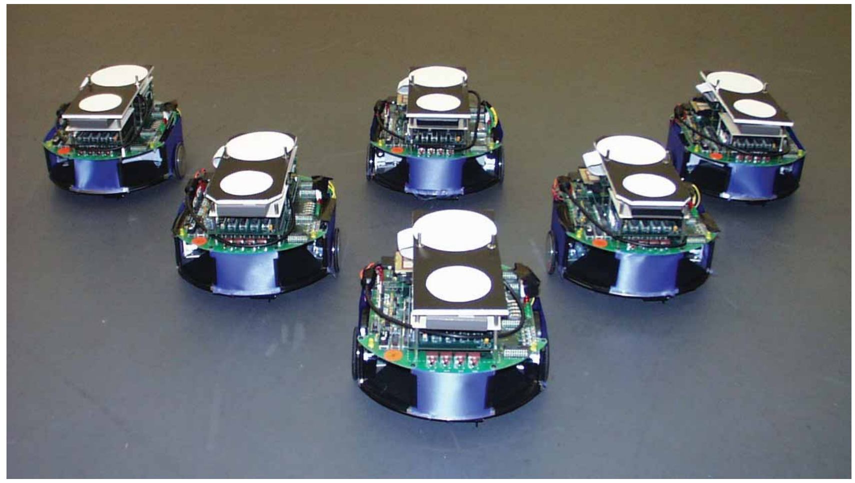
Scott and Antonsson, Preliminary Vehicle Structure Design: An Industrial Application of Imprecision in Engineering Design, *Proceedings of DETC '98* © American Society of Mechanical Engineers 1998

Good engineers develop a "feel" for such things, but quantifying them for a computer is a thorny problem. Things affect one another in ways often not reducible to simple formulas, and there's a horrible mishmash of units—in evaluating a minivan's performance, how do you relate pounds per square inch of tire pressure to miles per gallon of fuel efficiency? Some performance requirements may be graven in stone, such as EPA emission standards; while others may offer more wiggle room—the wheelbase should be 105 inches, give or take a handsbreadth; and let's not even talk about style or color, but looks matter too. Regardless of how well-engineered or cheap to manufacture, the design is a flop if nobody buys it, so purely aesthetic preferences such as sleek, wide windows must be incorporated as well. (Here a variable for the door post's position—the farther aft the post, the wider the window—would serve.) You tell the computer what you want by assigning a preference rating of 1 to the most preferred value of each variable, allowing the machine to compare the relative merits of all possible trade-offs. But if your desired cruising range is 400 miles per tank of gas, say, it's unrealistic to simply program that preference as $r \geq 400$, because 400.01 miles per tank would be perfectly acceptable, generating a preference rating of 1, and 399.99 would be completely unacceptable, scoring 0.

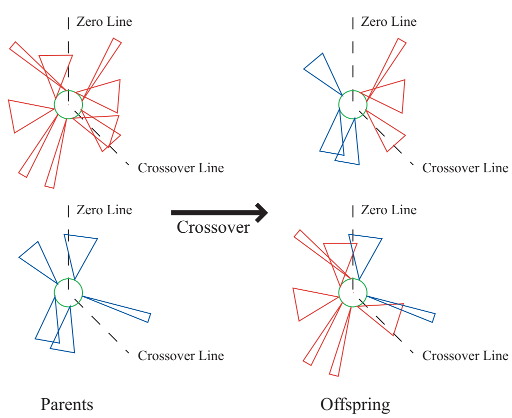
Antonsson and Kristin Wood (MS '86, PhD '90) introduced what they christened the Method of Imprecision, which replaced yes/no calculations with a provision for indicating the designer's and customer's degree of satisfaction with each intermediate performance level. Now the all-or-nothing stairstep became just a special case of a broader class of functions. The trick, of course, was to be sure all the variables were correctly selected and the preferences properly coded—not a trivial task. Then he and Kevin Otto (PhD '92) "formalized," or set up computer-friendly rules, for the process of analyzing trade-offs using the



Grad student Yizhen Zhang's collision-avoiding robots live in a computer, left. If she ever decides to study the real thing, this fleet of Moorebots, right, is available. Housed in the Moore Laboratory of Engineering, they are essentially PCs on wheels.



In the robot-anatomy sketch below, the triangles represent the sensors' fields of view. The "chromosome" for each robot begins at its zero line (facing dead ahead, in other words) and proceeds counterclockwise around its rim. Each sensor is encoded as four variables: position, look angle, range, and width of view. A crossover is tantamount to cutting the robots like wheels of cheese and trading the pieces.



mathematics of "fuzzy" sets. In a nutshell, the system multiplied each preference by a weight factor that reflected how important it was. Then the trade-offs were evaluated under various schemes—either "compensating," pitting head-room against gas mileage, for example, and finding their highest combined rating; or "non-compensating": you make any one bolt in the undercarriage too weak and the axle falls off. And he and William Law (MS '93, PhD '96) developed a system for creating hierarchies or "trees" of trade-offs so that you could, for example, analyze the safety margins of the load-bearing parts in a noncompensating way while independently balancing cost versus weight, and then combine those two results in another noncompensating calculation. Antonsson's group was the first to apply fuzzy math to engineering design; some half-dozen academic labs worldwide and several industrial ones, including at General Motors and Ford, have since taken it up. His own lab has looked at gas turbines; passenger-car bodies; and an aeroshell for a Mars penetrator similar to the two Deep Space 2 probes lost with the Mars Polar Lander, done with Robert Glaser (MS '71, Eng '73), a Member of the Technical Staff at JPL.

Examining every possible combination of potentially thousands of design and performance variables sucks up a lot of computer time, so three of Antonsson's current grad students are exploring evolutionary design, using the various design parameters as "genes." A computer creates random design configurations, each encoded as a sequence of numbers—the genes on the "chromosome"—and puts the designs through a series of simulations. Their performance in these simulations is then evaluated using the Method of Imprecision. The good designs are allowed to breed by "pairing" the chromosomes, cutting them somewhere, and swapping one of the two pieces in what biologists call a crossover. A chromosome may also get zapped by a random point mutation, and genes can even be added or deleted, changing the design's complexity. The offspring get evaluated against one another and against the survivors of previous rounds, ensuring that the population as a whole gets fitter with time.

Third-year grad student Yizhen Zhang (MS '01) is testing evolutionary design on a relatively complex problem by trying to find the optimum arrangement of sensors that will allow a "smart" car to avoid collisions with other vehicles. (Zhang is coadvised by Alcherio Martinoli, a senior research fellow in electrical engineering in Caltech's collective robotics group.) A proximity sensor's cost depends on its range and field of view, so for maximum coverage at minimum cost, is it better to have a few expensive sensors, a bunch of cheap ones, or something in between? Zhang uses a commercially available software package called Webots that models fleets of robots in a computer. Each trial has seven robots driving down a three-lane freeway—no oncoming traffic to worry about, in other words—changing lanes as needed to maintain their randomly assigned preferred cruising speeds, and braking when they have to in order to avoid collisions. One robot carries the sensor array; the rest are just traffic, and the Webot software pilots and tracks all of them from a helicopter, as it were. An invisible "bubble," called the detection region, surrounds the sensor-bearing robot. Whenever another robot penetrates the bubble, the computer determines whether the intruder passes through a sensor's field of view and is detected. When only one type of sensor is permitted, the simulations have evolved vehicles endowed with as many as 20 of them. But when the ranges and fields of view are allowed to vary as well, six to eight sensors suffice to register 99 percent of the vehicles entering the detection region. Zhang hopes to eventually use data from the sensors themselves to steer the vehicles, she says, but "right now the challenge is just to see how well the robot detects things in its environment."

Second-year grad student Fabien Nicaise is expanding on work other researchers originally did in two dimensions, in which the computer "grows" a truss that will support a load with a given margin of safety and a given degree of stiffness—and, eventually, for less than a given cost. (The system currently uses the weight of the beams as a proxy for their price.) The computation begins with a tripod and adds more legs, or changes their thickness, then decides whether the stiffness gained is worth the weight. The goal is to make the truss members smaller and smaller until they blend into a continuous solid, at which point the system would be able to evolve free-form shapes.

Third-year grad student Bingwen Wang (MS '01) hopes to automate the process that creates design genes by borrowing ideas from integrated-circuit design. When you design, say, a new memory chip, you tell the computer, "I want this region of the chip to perform this function to these standards," and the machine does the rest, using a recipe book of procedures called algorithms. Wang is trying to apply this notion of modularity to electromechanical systems. In a minivan, for example, the engine, chassis, and seats would all be modules. And you can have modules within modules—the engine includes the ignition system, the carburetor, and so on, and the ignition system contains spark plugs, which consist of….

Ideally, the computer would figure out the modules and their hierarchy automatically. This means you need a mathematical definition of modularity, which is not as simple as it might seem. "There are some intuitive definitions of modularity," says Wang. "But they do not include information flow." In other words, before you design something in detail, you sketch out how it is supposed to work. You write each function down, draw a box around it, and connect the boxes with arrows representing their interactions. For example, the ignition system has to fire the spark plugs at the correct rate for the engine's speed, which is determined by how hard you tromp on the gas pedal and regulated by a feedback loop that includes a vacuum sensor linked to the intake manifold. "Most definitions of modularity do not consider the attributes of the interactions, and only consider them as links." But the attributes exist—in this example, some of the interactions are electronic, some are mechanical, and some are fluid-mechanical, and this kind of information can be written along the arrows. There are many possible ways that the functions could be grouped into modules, so Wang is developing a set of algorithms that will use the arrows' annotations to find the grouping with the highest modularity.

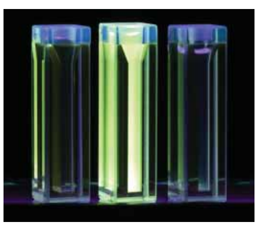
In nonevolutionary work, first-year grad student Tomonori Honda is expanding on Otto's treatment of uncertainties such as manufacturing tolerances (12-gauge steel can vary in thickness by half a millimeter—how does this affect the stiffness?), external factors (is it for use in Miami or the Antarctic?), and even wear and tear on the components. Otto evaluated one variable at a time, and then aggregated the results into an overall score for each design. Honda is aggregating related uncertainties into multidimensional calculations that can then be organized into a hierarchy, vastly reducing the amount of computer time needed. In the process, he's discovered that the methods of correlation chosen, and the order in which they are performed, can significantly affect the outcome.

And first-year grad student Lisa Dang wants to work on rocket engines powered by radioisotope thermoelectric generators, or RTGs. RTGs convert the heat from decaying plutonium into electricity that could run an ion drive, like that on JPL's solar-powered Deep Space 1. They power the instruments on spacecraft that fly too far from the sun to use solar panels, but today's models aren't strong enough to run a thruster. Dang is hoping to parlay Antonsson's JPL contacts into a research position in the RTG part of the Project Prometheus Program, which began funding in fiscal 2003.

Which brings us to the question, What does JPL's chief technologist actually *do?* The press release announcing Antonsson's appointment said he's responsible for "planning, implementing, and leading JPL's technology strategy" and "top-level coordination and assessment of technology work and infusion in flight activity," which translates into an endless string of meetings "driven largely," he says, "by the desire of some large fraction of the 5,000 people that work at the Lab to get a few minutes of my time to talk about something they feel is important for the chief technologist to know about." This takes some flexibility—on a recent morning, his 9:00 meeting started 15 minutes late and had to end 15 minutes early when out-of-town visitors showed up unexpectedly and needed to be worked in before the 10:00 meeting started. But the truncated half-hour meeting wound up taking 40 minutes; the 9:45 visitors became the 9:55 visitors and, when last seen, Antonsson's assistant, Annette Ling, was trying to get the 10:00 meeting postponed to 2:00, and the 2:00 switched to another day. There are administrative meetings, program-strategy sessions, technical discussions, and, in the odd free moment, mountains of reports to read.

The highlight of Antonsson's week is Tuesday afternoon, which he has set aside to play scientific tourist. "I get to actually go out and see the technology that various groups on Lab are devel-

A small sample of JPL's advanced technologies. This "spiderbot" prototype, left, fits in the palm of your hand, and its forelegs can grip and lift twice its body weight. Someday, a squad of sophisticated spiderbots might roam the surface of Mars in search of life. Such 'bots might store energy in ultra-light wafer batteries, below left. And before leaving Earth, they might be checked for sterility by an automated process that generates a fluorescent signal when spores are present, bottom left. Antonssons' bailiwick also includes developing non-hardware technologies, such as swarm intelligence and autonomous systems that can "think" for themselves.



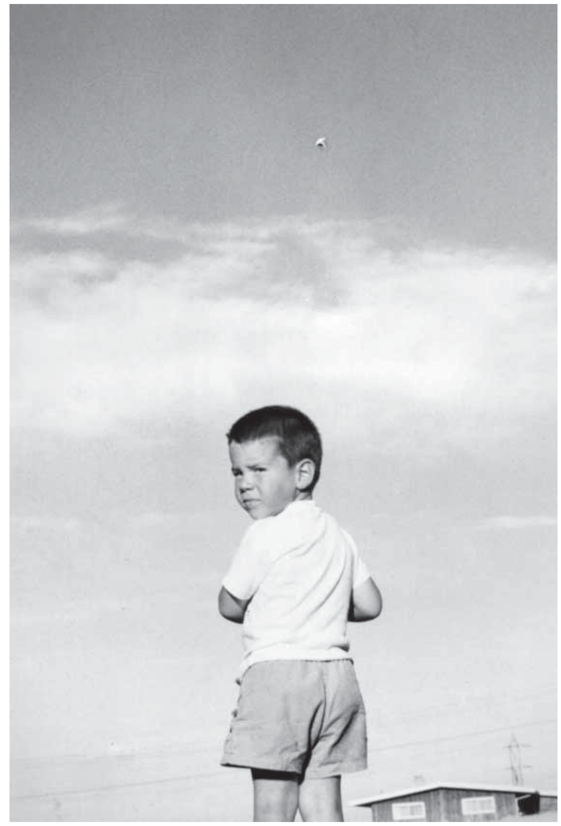
oping. And those are *wonderful*. I love those lab tours because I see dedicated people, excited by the work they're doing, in their native habitat. Right there with the oscilloscopes and vacuum chambers, and all the *stuff*."

The point of all these meetings is to become a technological handicapper, in the racetrack sense of the word. Antonsson and Chief Scientist Tom Prince (a Caltech professor of physics) manage JPL's Research and Technology Development Fund, which amounted to some $10 million in fiscal '03, and which JPL's director, Charles Elachi (MS '69, PhD '71), has pledged to increase to around $50 million over the next several years. It's a drop in the bucket compared to JPL's roughly $1.5 billion budget, but "it's a pivotal fund," Antonsson says. "It's the Lab's venture capital—the fund for speculation, to say, 'Hey, I've got an idea for a totally new sensor. I'd like some money to see whether it will really do what I think it'll do.'" If the idea pans out, it can then be written into the mission profile of a spacecraft on the drawing board, and its development becomes part of that mission. "Job one for me is building a strategic plan for advanced technology: where should the Lab be putting its resources to be most effective in developing the most important—strategically important—technologies for its future? What can be done to best position us to accomplish the missions that, as a group, the Lab feels are most important? I've organized a working group of technologists, and we hope to have a first draft of a plan pretty soon." At the moment, it's more a set of bullet points than a document.

Not all meetings are at JPL. Antonsson is JPL's senior representative for technology research to the rest of NASA, to the White House Office of Science and Technology Policy, and to other techno-agencies. He's been to NASA Headquarters in Washington four times already, and expects that a couple of two- or three-day trips a month—to any of a number of places—will be the norm; as a father of three school-age kids, he's hoping it will be no more than that. Some excursions are more science-touristy, like the day he spent at the Air Force Research Laboratory in Dayton, Ohio. He also plans to drop in on corporate labs. "I got an invitation from Ball Aerospace to help review their internal R&D program, which I had to decline. But I'd be delighted to participate in the future, given more notice, so that the Lab is well-informed about the most advanced technologies that these contracting organizations have available." Another "part of my job is university relations in general, and Caltech and the engineering and applied science division in particular. There are many opportunities for collaboration, but the two institutions have dramatic differences in mission."

Antonsson spends every Thursday on campus. He's disentangled himself from most of his faculty commitments—executive officer for mechanical engineering, director of the Engineering Computing Facility, and memberships on the engineering and applied science division steering committee, the division advisory group, and the Caltech/MIT Voting Technology Project. He is, however, retaining his seat on the faculty board to keep the information pipeline to campus open. And the ME 72 contest will go on, as will the other courses he teaches in various aspects of design and kinematics. He's brought in a "really great" design instructor, Maria Yang from Stanford, along with Karl-Heinrich Grote, a visiting professor from Otto von Guernicke University in Magdeburg, Germany, and visiting associate Curtis Collins from UC Irvine, to teach and to help run his lab. "I've been telling them where all the bones are buried and how things work. So I'm still involved in teaching, and it isn't that I *want* that to go to zero, but I'll have to try to make it as close to zero as I can." He's trying very hard to devote his campus time to keeping his own lab from becoming just another roadside attraction on one of his

From the grad students' point of view, meeting with their advisor just once a week seems to be working out pretty well. "You only have to stress one night a week about your work, rather than every night," says Honda with a grin.



At an early age Antonsson was already prototyping devices for high-altitude research. Or would be, if Dad would just leave him alone...

scientific tours. "The ideal is that I pare back everything except advising my graduate students. My goal is that the research in my group will continue at much the same pace as it had been; I'm enough of a realist to know that it will be imperfect, but it's the best I can do. As I say to people who ask how it's going, I used to have one completely overwhelming 50+ hour a week job as a Caltech faculty member—now I have two."

From the grad students' point of view, meeting with their advisor just once a week seems to be working out pretty well. "You only have to stress one night a week about your work, rather than every night," says Honda with a grin. Says Wang, "A half-hour meeting every week seems to be enough time to get everything done. And this gives me freedom to develop ideas on my own." It might be different if the students were building physical structures, but since all the work is done in simulations, the only thing that can come crashing to the ground is the computer. And if an idea really goes south, Antonsson is only a phone call or an e-mail away.

Antonsson is now roughly a quarter of the way into his two-year leave of absence—time spent mostly in learning how the Lab works and how to speak NASA. In the political world, the first term in office is usually just about enough time to get fully acclimated, so has he given any thought to extending his leave, or going up to JPL permanently? While interviewing for the job, he talked to Ed Stone, Morrisroe Professor of Physics, director of JPL from 1991 to 2001, and project scientist for the Voyager missions [see page 10]. "He was quite influential in convincing me that this was a position that I really should accept. He also said that he thought two years was about right, but probably a little short. I'll be learning and learning and learning, and at the end of that two years, I would be educated sufficiently to be valuable to the Laboratory, and that I would find myself under some pressure to stay. I can only hope that comes true. And he said that I may well want to stay on for a *little* bit longer than two years, but he recommended that I absolutely not stay on longer than three because the rate at which I will be learning new things will decrease. He also said that my position on campus—students knowing me, my position in campus life and politics—would also decay with time, and that if I am away more than three years it would be really detrimental. And I've taken his advice to heart."

Meanwhile, Antonsson's academic specialty has proven a real advantage in his role at JPL, because "engineering design inevitably draws from many technologies in the course of solving the problem at hand. So the people involved in engineering design tend to be conversant in a variety of technologies, in order to be able to know when and how to use them. And that's what the chief technologist does." And his stint at JPL is providing insights he'll be able to use in his own lab. "JPL as an institution designs and builds incredibly complex systems, so I have the opportunity now to see how these design problems are solved in the real world, what strategies work, how performance requirements are integrated, and how different constituencies negotiate trade-offs with one another, and that will help inform the research that I will do going forward." □

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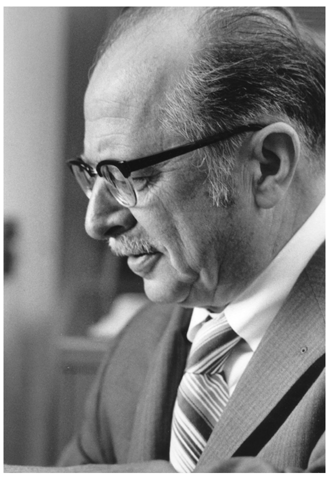
Jesse L. Greenstein 1909 – 2002



Jesse L. Greenstein, the DuBridge Professor of Astrophysics, Emeritus, died last October 21, three days after falling and breaking his hip. He was 93.

Greenstein grew up in New York City in a family that encouraged his scientific interests. He entered Harvard at the age of 16, where he earned his bachelor's degree in 1929 and master's in 1930, and (after a stint in his family's real estate and finance business during the Depression) his PhD in 1937, with a thesis on interstellar dust.

It was as a 16-year-old undergraduate at Harvard that he met his wife, Naomi, who died earlier last year after a marriage of 68 years. At the memorial service in Dabney Lounge February 11, Professor of Astronomy Anneila Sargent, who presided, noted that "we're here to combine our memories to make a lasting picture of a remarkable man and a remarkable life." And, she added, "It's hard for many of us in this room to say just 'Jesse'; it's often Jesse and Naomi."

After Harvard, Greenstein joined the University of Chicago's Yerkes Observatory, first as a postdoc and after 1939 as a member of the astrophysics faculty. When he came to Caltech in 1948 to organize a new graduate program in optical astronomy in conjunction with the new 200-inch Hale Telescope on Palomar Mountain, he brought a lot of Yerkes with him. At the memorial service, Donald Osterbrock, now professor emeritus at UC Santa Cruz and Lick Observatory, recalled "how he was a product of his 11 years at Yerkes Observatory." Greenstein built the Caltech department, mostly out of Yerkes PhDs, one of whom was Osterbrock, who came in 1953. "Jesse was my first boss . . .Best boss I ever had," he said.

Osterbrock illustrated his remarks with slides of meetings and conferences from the '30s and '40s showing the young Greenstein with most of the great names in early 20th-century astronomy. "As a young student, postdoc, and junior astronomer, Jesse was inspired by all those research scientists, but in his turn, he inspired a whole new generation of outstanding research astronomers and astrophysicists here at Caltech," he said.

Robert Kraft, who, like Osterbrock, is professor emeritus at UC Santa Cruz and Lick Observatory, surveyed briefly Greenstein's lifetime of work ("just about everything in astrophysics"), published in more than 400 papers. This work ranged from his initial interests at Harvard to his turn toward high-resolution stellar spectroscopy at Yerkes, the famous project from 1957 to 1970 on abundances of the elements, and later, after he "retired," his study of white dwarfs. Kraft noted Greenstein's generosity on the issue of author order on papers: "In most of the abundance papers, Jesse is almost always not the first author; he generally stepped aside, permitting his younger colleagues to have their place in the sun.

"Jesse was one of the great figures of American astronomy in the 20th century," said Kraft, who, as a Mount Wilson observer in the '50s and'60s, had "family status" at Caltech during what Kraft referred to as the "famous days of the Mount Wilson and Palomar Observatories."

Jerry Wasserburg, the MacArthur Professor of Geology and Geophysics, Emeritus, recalled meeting the Greensteins in 1955 when he was a new assistant professor. "The hospitality in the Greenstein home was fabulous," he said, with both Jesse and Naomi offering a "liberal education to us technocratic characters to improve our view of life"—an education in things like art and wine.

Lunches at the Athenaeum also remained firmly in Wasserburg's memory—Greenstein's elegant Schimmelpfennig cigarillos and Willy Fowler's cheap mentholated cigars; Greenstein turning over the placemats: "He would pull a pen out from his vest immediately upon any argument and cover the placemat with incisive calculations, where numbers in many powers of 10 would appear and disappear in some wonderful juggle. And you were trying to follow it from across the table."

Wasserburg mentioned Greenstein's view of the famous paper on element abundances by Burbidge, Burbidge, Fowler, and Hoyle, popularly known as B^2FH: "The B^2FH business was full of conflicts for Jesse. He knew and thought this was all-important, and he was a big supporter and contributor to that effort. But having a bunch of nuclear physicists who did not know any *real* astronomy say where the elements came from, which he had been measuring, while he was trying to measure them and at the same time trying to educate these nuclear physics savages into real astronomy, was painful to him."

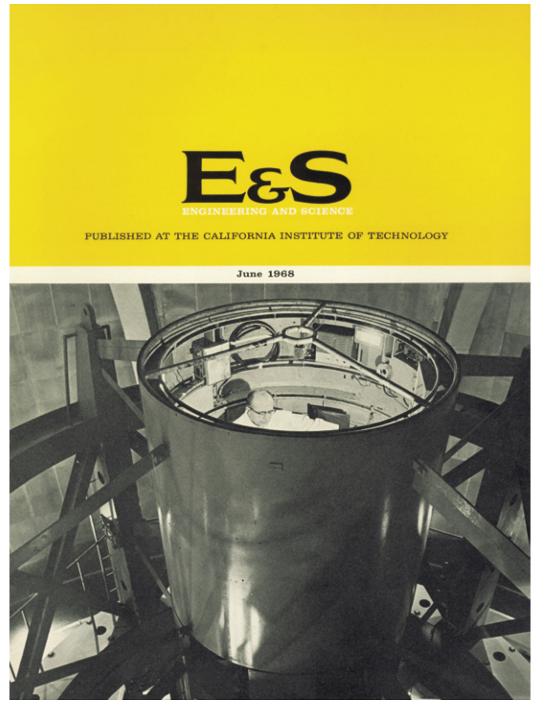
Besides nuclear physics, Greenstein was also interested in radio astronomy. Marshall Cohen, professor of astronomy, emeritus, who joined the Caltech faculty in 1968, noted that Greenstein wrote a paper on radio astronomy in 1937 while he was a grad student at Harvard, in the days when most optical astronomers were indifferent to the field. This changed, said Cohen, in 1951, when a compact radio source was first identified with a distant galaxy. "This excited Jesse, and he began to lobby the Caltech administration to set up a radio astronomy program," he said.

"Jesse organized the famous conference at the Carnegie Institution in Washington, in January 1954," recounted Cohen. "That meeting catalyzed the founding of the National Radio Astronomy Observatory and Caltech's Owens Valley Radio Observatory. OVRO was dedicated in 1958 and quickly became one of the premier institutions in the country."

Greenstein also played a part in the discovery of quasars. Maarten Schmidt, the Moseley Professor of Astronomy, Emeritus, recalled the fateful afternoon exactly 40 years ago when he suddenly discovered that the spectrum of a radio star, 3C273, showed a redshift of 16 percent. "I was stunned," he remembered. "Could this bright star really be at a distance of a billion light-years? Pacing back and forth, I saw Jesse in the hallway and told him what had happened. After a while Jesse got his observations on 3C48 [the first discovered radio star], and in 10 or 15 minutes, we succeeded in finding that it had a redshift of 37 percent. We made so much noise in discussing the consequences that Bev Oke came in to find out what was happening. We tried to find alternative explanations that would not require a redshift at all, but we failed. By the end of the day, the three of us were off to the Greenstein house, where Naomi was astounded when we all had a stiff drink. That was the beginning of quasars in astronomy."

About the article they subsequently wrote, Schmidt said, "Some of the parts Jesse wrote are breathtaking, even to me. . . . I think it was probably the most exciting scientific venture in his life."

Radio astronomer Anneila Sargent, who had been a graduate student during Greenstein's reign, pointed out that he was "way before his time" in bringing in female grad students. "There were more women in astronomy by percentage than in most of the other divisions at Caltech. Jesse was often teased about it," she said. She was also Greenstein's research assistant for a number of years and collaborated on his 300th paper. Sargent is a past president of the American Astronomical Society, as are Osterbrock, Kraft, and Schmidt.



Greenstein also loved music and art. His younger son, Peter, spoke at the memorial of growing up in a household filled with all kinds of classical music, but "in the latter part of my father's life, he narrowed his interests down to chamber music, lieder, and opera," he said. He admired the string quartets of Hayden, Mozart, and Schubert, but reserved his highest reverence for those of Beethoven, especially the last quartets. Peter then introduced a quartet of string players, who performed the *Cavatina* movement of Beethoven's Quartet no. 13, op. 130. His brother, George, noted later that this movement is included on a disk headed for space aboard Voyager 1 (see page 17).

Greenstein owned an extensive collection of Japanese paintings and prints and was a member of the board of trustees of Pasadena's Pacific Asia Museum. David Kamansky, director of that museum, spoke of how they had become fast friends through their mutual interest in Japanese painting. Greenstein gave most of the collection that was displayed in his home to the Pacific Asia Museum when he and his wife moved into a retirement home with far less wall space.

"The final gift of paintings from Jesse, his favorite ones, was given only a few months before his death," said Kamansky. "He'd kept them to enjoy, under his bed, where he would take them out for anyone interested in seeing and talking about them. He told me he enjoyed them for many years, but now it was time to place them in the public trust, where they would be enjoyed by generations to come and studied and learned from."

Kamansky noted a particularly favorite painting of Greenstein's. "The signature says 'Katsushika Hokusai, an old man mad about painting.' And I think of Jesse in the same way."

Elder son George Greenstein, also an astrophysicist, remembered his mother's Playreaders, a group she helped found, and noted that astronomy played only a walk-on role in the Greenstein home: "It made just brief appearances in the family life. It was certainly important, but maybe not that important."

George Greenstein said that his father "loved observing. It's very sad nowadays that people don't really observe." And he quoted something his father had written about astronomical observing: "This is not a normal way of life. Very few people in the world do the same thing, but for all my unknown colleagues in some other dawn on another mountain, thoughts will be similar. There is a deep content at having been awake with the universe, at watching the faint glow of some part of it. Possibly I have tonight even asked it an important question."

He also remembered a question he had asked his father very late in his life about a "dirty little secret of science": "What do you do if you just can't do it, if you don't know how to solve that problem? And what he said, very quietly and peacefully, was, 'I always knew I could do it.'"

Granddaughter Ilana Greenstein recalled a number of anecdotes of the grandfather she had gotten to know well only as a teenager, having grown up on the opposite coast. "Jesse lived his life in a state of constant anxiety, constant friction, constant discontent," she remembered. "He was a dark, complicated, dazzling person, but there was a sweetness to him."

She talked about the last time she saw him, last July, when, uncharacteristically, "he didn't seem to need time to rest. And it was the first time I had ever seen Jesse at peace. He wasn't worried; he wasn't anxious; didn't have any interest at all in the things that had always dominated his conversation before. He didn't want to talk about politics or the stock market or the space-time continuum or his memories of the past. He just lay back on his pillows, smiling and relaxed, and all he wanted was to hear us talk. He seemed to be happy, happy to be fading out of the world, secure in the knowledge that it would spin on in all of its joy and mystery without him. He looked contented for the first time I can remember." □ —*JD*

Wheeler J. North
1922 – 2002

Wheeler J. North, professor of environmental science, emeritus, died on December 20. He was 80.

Born in San Francisco, North moved with his family soon afterward to San Diego, where he began exploring tide pools at the age of seven. He also developed an early interest in kelp beds, which would turn out to be his life's work.

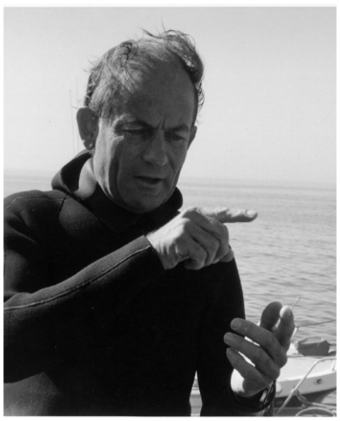
North received his first BS (in electrical engineering) from Caltech in 1944, then returned to Pasadena after the war to earn a second one, in biology, in 1950. His MS and PhD are from the University of California (1953). After several years at Scripps Oceanographic Institution, he returned to Caltech in 1962, first as visiting professor of biology, then as associate professor of environmental health engineering, and finally as professor of environmental science.

Although he taught a popular marine biology course (among others) on campus, North spent much of his time working out of Caltech's Kerckhoff Marine Laboratory in Corona del Mar, studying the complex ecosystem of the giant kelp (*Macrocystis pyrifera*) off the California coast. He determined that the kelp beds were shrinking as sewage fed the sea urchin population, which in turn fed on the kelp. He also studied the effect of humans on kelp, in particular the warm-water discharge from the San Onofre nuclear power plant, which deterred kelp development; and oil spills, an environment in which kelp thrive. He devised techniques for restoring and farming kelp forests.

North was one of the pioneers of scuba diving for scientific research, making his first dive in 1949. He purchased one of the first 10

Aqua-Lungs sold in the U.S.; since wet suits did not yet exist, he put on woolen underwear.

In 1972 North described his work to *National Geographic*: "At day's end, I often relax by lazily roaming the upper branches of the tall forest where I work. Creatures bizarre and beautiful swarm about me. Overhead, the tangled foliage almost obscures the daylight. But I need no tree climbing irons; only swim fins. The air I breathe is carried on my back. I am a scuba forester and the 'trees' I tend are giant vine-like streamers from the ocean floor off Southern California."



A memorial service was held on February 22 at the Ocean Science Center in Dana Point, where friends, colleagues, students (including five of his ten PhD students), and family gathered to reminisce and "tell Wheeler stories." Chuck Mitchell, president of MBC Applied Environmental Sciences, who organized the occasion and presided over it, told of meeting North in 1955, after lying about his age ("I told everyone I was 16") to get a summer job at Scripps. 'He was unique," said Mitchell. "He had life-changing, life-directing effects, and we probably didn't even know it at the time. We have all been spread over time and space, and I'm glad that we have the opportunity to get together here today to compare notes on this phenomenon."

Mitchell, who was also one of the pioneer divers, recalled his friend's optimism, curiosity, and patience; the "stratigraphy" of his desk, files, and storerooms. With slides as illustrations, he reviewed some of North's familiar characteristics (to much amused laughter): his early, self-made diving gear, his shoes with flapping soles, the patches on his wet suit (he used to hold his suit together with bits of old underwear), his string of decaying, uncared-for automobiles and boats, and an ancient tuxedo with a hole in the knee ("he was going to paint his knee but got the hole mended").

Jim Morgan, the Goldberger Professor of Environmental Engineering, Emeritus, had a very clear memory of his "job seminar" as a prospective faculty member in 1965: "Sailing along talking about particles and polymer chemistry and God knows what else, I happened to look down at the first seat in the front row, only to see Wheeler sound asleep! I wondered, was my future academic fate already sealed?" He was assured by a colleague afterward that Wheeler always slept through seminars ("I think it's all that scuba diving"), and "that was the beginning of a 38-year beautiful friendship." And reciprocity—"Wheeler would sleep through most of my seminars, and I would sleep through his."

Morgan noted North's "visionary pursuit of an idea for 'kelp farms' for energy generation," and another idea (on which Morgan had collaborated as an aquatic chemist) for forming carbon dioxide hydrate solids in seawater, which North envisioned as a potential process for storing carbon dioxide from combustion in power plants in deep coastal waters. Morgan also showed slides, including the *E&S* cover shown on the previous page, and the 1972 *National Geographic* cover ("when very few people were even using the words 'environmental science'"); also pictures of North "obliterating sea urchins with a hammer," introducing new Caltech undergrads to his ice chest full of sea creatures at Freshman Camp, and dressed in a tuxedo as Morgan accepted the Clark Award three years ago.

Another pioneer diver, who became Scripps's diving officer and helped spread the techniques of scientific diving, was North's friend Jim Stewart. He joined Scripps as a volunteer diver in 1952 and helped start the kelp study project with North—"over the years we've moved a lot of kelp." He told anecdotes of storms and rescues in the *Orca*, a converted yacht, and fishing for dinner off the back of the boat. "Wheeler and I worked together on a lot of projects, conducted an awful lot of studies, and had a lot of fun," said Stewart.

One of his fondest remembrances was what Stewart called the "Tampico days." In 1957, the *Tampico Maru*, a 360-ft. tanker out of San Pedro, went one degree off course, and "put that thing right up there on the rocks at 4 a.m.," spilling about 20,000 barrels of diesel oil into a small cove. North and his team arrived soon thereafter to study what happened to the marine life and found that the oil killed all the animals that grazed on the kelp, allowing a vast kelp forest to flourish. North and his colleagues studied its growth, and published the first data in 1964 and several papers thereafter.

"Compared to other spills,

the *Tampico Maru* was right up there with them—huge," said Alan Mearns, senior staff scientist with NOAA (National Oceanic and Atmospheric Administration). "It was the largest diesel spill on the West Coast and the first spill followed by longterm biological monitoring." Before leaving for NOAA's oil spill team in Seattle, Mearns had worked with North in the '70s on the Southern California Coastal Water Research Project, surveying the coast for water pollution from Point Conception to the border.

When Mearns and North ran into each other again in 1997, Mearns realized what a wealth of data North had collected in the aftermath of the *Tampico Maru*. "This was an important spill because it was a diesel spill. We had very few cases of documented diesel spill and effects, and here we had 20 years of documented study." North got his unpublished data together, and NOAA will shortly publish a technical memo under North's name on the 20-year history of records from the *Tampico Maru*. "I have to help finish this particular part of the story that Wheeler began," Mearns concluded.

Lee Peterson, BS '64, MS '66, PhD '74, was a graduate student of North's, whom he credited with the inspiration to learn to fly, as well as dive (flying was another passion of North's). He fondly recalled flying out to a site, diving, then getting on the airplane again and going up to 10,000 feet. "That's really a no-no," he said. "Sometimes my nails were getting blue." He spoke of towing kelp plants from Newport to Palos Verdes and tying them to chains underwater. The air in the crew's tanks lasted about 45 minutes, "but Wheeler would be out for two hours on one tank," said Peterson. "To this day, I don't understand how he could last so long. But he was so relaxed, and he loved being down there so much, maybe he just didn't breathe."

North's family joined in the remembrances. Brother-in-law Dennis Moyer (whose remarks were read in his absence by his wife, Elizabeth Best Moyer) offered his own "brushstroke" to the other "elegant, revealing, and often humorous brushstrokes that create this most personal portrait of Wheeler." Moyer remembered North's "impishly fine wit" and "loved the fullness and patient clarity with which he answered my questions about his work." He also noted his selfless devotion to their mother-in-law toward the end of her life. "I, we, will be eternally grateful for his singular sense of familial duty, friendship, and love."

North's wife, Barbara, described the "family airplane." When he couldn't get anyone else to photograph the kelp beds from the air, "he went and bought an airplane," and Barbara got her own pilot's license before she would set foot in it. When he realized that it's hard to take pictures from a low-wing plane, North "cut two huge holes in the bottom of the plane, one under each seat, so you could look down. I don't think the FAA ever knew what we had done to this plane."

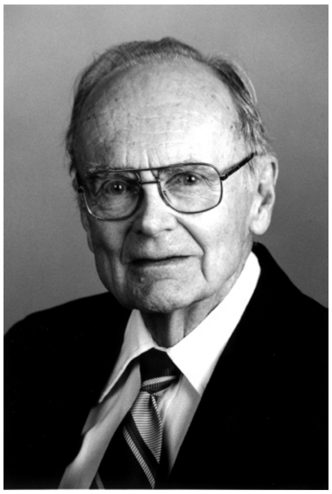
Like several of the other speakers, Barbara had met Wheeler at the Scripps student summer program, where she also dove to study the kelp beds and hung around to spend thousands of hours underwater. Eventually, "Wheeler incurred the displeasure of some of the senior research staff at Scripps by pointing out to them that perhaps it was more effective to actually go into the kelp bed and study it instead of sitting on a boat deck and speculating about it. Caltech understood that perhaps the direct approach was better and stole him away from Scripps. He was forever grateful about that."

"When I was a kid," said North's son, also named Wheeler, "if you were going to do something with Pop, that meant that you got stuck in the back of an [open] truck on top of a big pile of gear and ropes, and you were tied in and spent four or five hours watching the world go by backwards. And eventually, you got to some really neat place and spent a couple of weeks running around, but learning a lot about life and science." His father, he said, exuded happiness and brought out happiness in others: "We would walk down the street, and people would walk by and just start smiling."

Wheeler North, Sr., loved limericks, so his son read a long limerick that he had composed for the occasion, "A Poem of a Sort about Wheeler J. North," which began: "There once was a man named Whee/ Deep secrets he teased from the sea. . . ." and went on to tell the story of his father's life in numerous, humorous stanzas.

At the end of the ceremony, it was announced that the Southern California Academy of Sciences was establishing the Wheeler North Award for Scientific Excellence. "The recipient of the Wheeler North Award will have demonstrated commitment to research that emphasizes the Southern California area and a commitment to the Southern California scientific community." □ *—JD*

William R. Sears
1913 – 2002



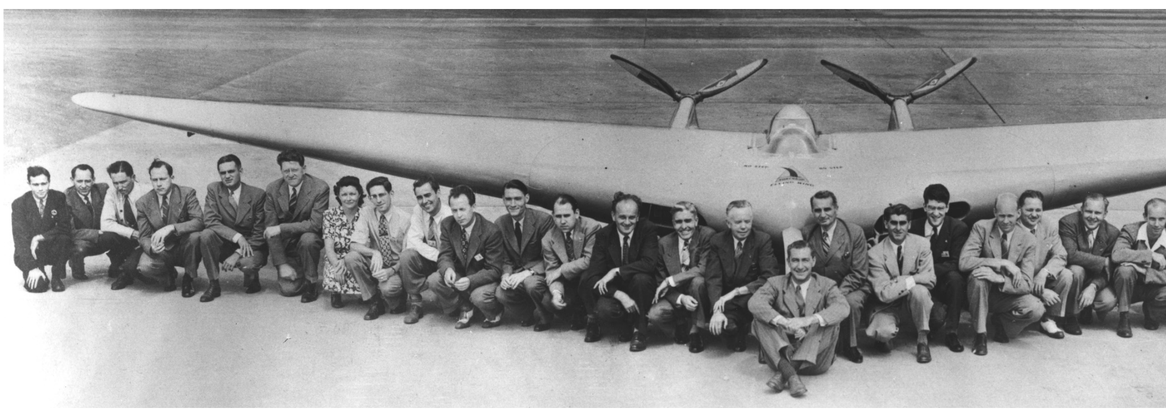
William Rees Sears, one of Theodore von Kármán's earliest and most renowned doctoral students at Caltech, died on October 12, 2002, in Tucson, after a brief illness. Sears held the position of Emeritus Professor of Aerospace Engineering at the University of Arizona at the time of his death.

Sears was born on March 1, 1913, in Minneapolis, the son of William and Gertrude Sears. He earned his BS degree from the University of Minnesota in 1934. Following the recommendation of his advisers, he moved to Caltech to study under Theodore von Kármán, who, five years earlier, had agreed to become the permanent director of the Guggenheim Aeronautical Laboratory (GALCIT). Upon his arrival, he was struck by the personalities and the warmth of von Kármán and his secretary, Mabel Rhodes. He worked diligently for the first and married the second. These two individuals, in their own ways, greatly influenced his life and career. Sears was awarded his PhD in 1938, writing a remarkable thesis concerning airfoils in nonsteady motion, a classic work that laid the foundations for future developments in that field.

In 1937, Sears had been appointed instructor in aeronautics, and in 1940, he was promoted to assistant professor. Through von Kármán's friendship with Jack Northrop, Sears became involved in some of the aerodynamic problems at Northrop Aircraft Corporation, and in 1941, with the United States' entry into World War II becoming more evident, Sears accepted Jack Northrop's offer to be chief of aerodynamics and flight testing.

The next five years at Northrop presented an abundance of opportunities for Bill, but none more exciting than heading the team that designed the first Flying Wing aircraft and the P-61 (the so-called Black Widow). Near the end of the war, Bill was appointed, as a civilian expert, to a Navy group that was to visit and debrief German engineers and scientists. He did not mention to the Navy that he was a naval reserve lieutenant; if he had, he would have traveled under much less comfortable circumstances than he did.

Despite Jack Northrop's strong assurance that he had a bright future in industry, Sears chose to return to academic life in 1946. He joined the faculty of Cornell University as the founder and first director of its Graduate School of Aeronautical Engineering. Bill's technical excellence and magnetic personality assured his success in building an outstanding faculty and in attracting a highly competent and devoted student body. Within a surprisingly few years, the Cornell Graduate School of Aeronautical Engineering was ranked among the world's best. He and his many students pioneered research in wing theory, unsteady flow, magnetohydrodynamics, and sophisticated wind tunnel design to study transonic flight. For many years, the administrative team of the GSAE consisted of Sears and his highly capable and unflappable secretary, Alice Anthony. He remained very close to von Kármán, who was a frequent visitor to the Cornell aero school. In 1962, he was named the J. L. Given Professor of Engineering, and in 1963, he decided it was time for a change and stepped down as director of the aero school after 17 years. In 1962, he founded and became director of Cornell's Center



Northrop engineers pose with the first Flying Wing in September 1943. Sears is fourth from right. Von Kármán is just to the right of the nose of the plane.

of Applied Mathematics.

After 28 years at Cornell, Sears joined the faculty of the department of aerospace and mechanical engineering at the University of Arizona in 1974. Four years later, he was named emeritus professor but remained an active faculty member and completed much of his important analytical and experimental work on adaptive-wall wind tunnels during these years.

Sears was a member of the National Academy of Sciences, the National Academy of Engineering, the American Academy of Arts and Sciences, and Mexico's Academia Nacional de Ingeniería. He was an honorary fellow of the American Institute of Aeronautics and Astronautics and was editor of the *Journal of the Aeronautical Sciences* from 1955 to 1963. During his lifetime, he received many honors and awards, including the Guggenheim Medal and the Prandtl Ring of the German Aeronautical Society. In 1988, Caltech gave him its Distinguished Alumni Award. He was also named an outstanding alumnus of the University of Minnesota and was awarded an honorary doctorate from the University of Arizona.

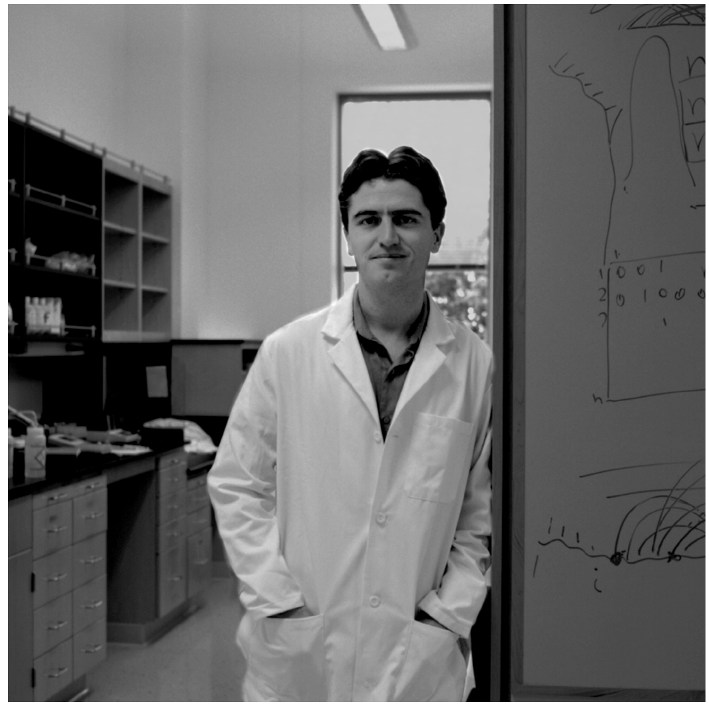
When Sears was a junior faculty member at Caltech, he was asked to direct the Civilian Pilot Training Program, a federal program that offered young people the possibility of earning a private pilot's license and receiving preparation for possible military flying in the event that the United States entered the war. Bill not only administered the program but took the opportunity to get his own license. Although his work at Northrop offered him little opportunity to fly, his move to Ithaca provided the incentive. In more than 50 years as a private pilot, he logged 8,000 hours before retiring from flying in 1990. He owned several small airplanes over the years, the last one his beloved Piper Twin Comanche.

Sears was also an accomplished musician, first as a percussionist. He worked his way through college as a drummer in dance bands and, after moving to California, was tympanist with the Pasadena Symphony for a couple of seasons. Later, at Cornell, he became an expert recorder player with a university group interested in medieval music. He played with the Collegium Musicum at the University of Arizona for 20 years.

He is survived by his wife, Mabel, of Tucson; their daughter, Susan Sears, of Indianapolis; son, David Sears, of Bethesda, Maryland; and grandchildren Colin and Shelby Sears, of Portland, Oregon. He also leaves many friends, colleagues, and former students, whose lives he touched and enriched.

William Rees Sears cast a bright, stimulating, and cheerful light on countless people around the world, a light that will be sorely missed. □

Frank E. Marble,
Hayman Professor of Mechanical Engineering and Professor of Jet Propulsion, Emeritus



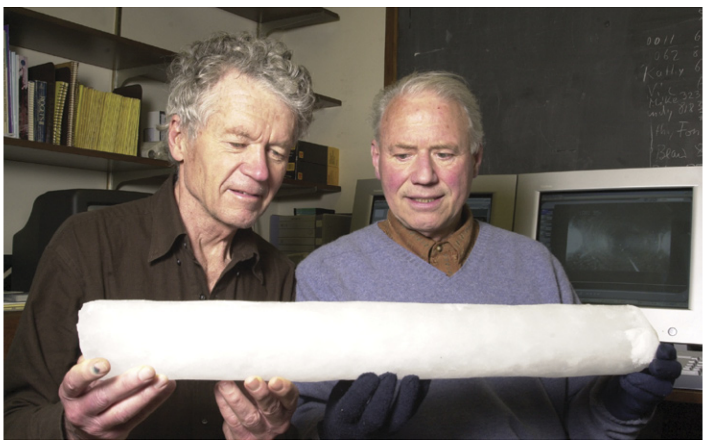
Niles Pierce, assistant professor of applied and computational mathematics, was awarded the 2003 Richard P. Feynman Prize for Excellence in Teaching, which carries a cash award of $3,500 and an equivalent raise in salary. According to the citation: "He teaches without oversimplifying and without intimidating, making the material accessible to the diverse group of students. He possesses an uncanny ability to anticipate the frustrations and challenges of the students, and has been able to hold the students' attention, and attendance, throughout the quarter."

Honors and Awards

Paul Asimow, assistant professor of geology and geochemistry, has been selected to receive the F. W. Clarke Award, which "is given to a young scientist in recognition of a single outstanding contribution to geochemistry or cosmochemistry, published as a single paper or a series of papers on a single topic." The award will be presented during the plenary session of the 2003 Goldschmidt Conference in Kurashiki, Japan. In addition, the Alfred P. Sloan Foundation has chosen Asimow for a Sloan Research Fellowship. "Coveted as an extraordinarily competitive award, the Sloan Research Fellowship carries with it a grant of $40,000 to be used in a flexible and largely unrestricted manner so as to provide the most constructive possible support of the professor's research."

John Baldeschwieler, the Johnson Professor and Professor of Chemistry, Emeritus, and a former chairman of the Division of Chemistry and Chemical Engineering, has been named corecipient of the Chemical Heritage Foundation's 2003 Othmer Gold Medal, to be presented on Heritage Day, June 12, in Philadelphia, at the Seventh Annual Othmer Gold Medal Luncheon. The medal honors "outstanding individuals who, like Donald Othmer (1904–1995), have made multifaceted contributions to our chemical and scientific heritage through outstanding activity in such areas as innovation, entrepreneurship, research, education, public understanding, legislation, or philanthropy."

Jack Beauchamp, BS '64, the Ferkel Professor of Chemistry, has been named the recipient of the American Chemical Society's 2003 Frank H. Field and Joe L. Franklin Award for Outstanding Achievement in Mass Spectrometry. The honor, which recognizes Beauchamp's development of "innovative ways to analyze molecules, methods that can help track pollutants in the environment, identify compounds in space, and detect explosives," will be presented on March 25, at the society's national meeting in New Orleans.



Barclay Kamb (left), the Rawn Professor of Geology and Geophysics, Emeritus, and Hermann Engelhardt, senior research associate in geophysics, emeritus, have been honored by the American Advisory Committee on Antarctic Names with the renaming of two features near the gigantic Ross Ice Shelf. What was formerly called "ice stream C" will now be formally named the Kamb Ice Stream, and "ice ridge BC" will become the Engelhardt Ice Ridge. The two have collaborated for years, studying the relatively rapid movement of Antarctica's ice streams (see E&S, Spring 1990), boring holes to their base to determine temperature and pressure. Here they hold an ice plug from one of the boreholes.

Scott Fraser, the Rosen Professor of Biology, is receiving a Space Act Award from the Strategic Intellectual Assets Management Office, for his work on "Two-Photon Microscope Imaging Spectrometer for Multiple Fluorescent Probes." The award includes a check for $3,200.

Harry Gray, the Beckman Professor of Chemistry and founding director of the Beckman Institute, has been selected to receive the National Academy of Science Award in Chemical Sciences. He is being recognized "for his demonstration of long-range electron tunneling in proteins, his inspirational teaching and mentoring of students, and his unselfish service as a statesman for chemistry."

Cathy Jurca, associate professor of literature and master of student houses, has had her book *White Diaspora: The Suburb and the Twentieth-Century American Novel* chosen by *Choice* magazine as one of its Outstanding Academic Titles of the past year. *Choice*, which reviews books, electronic products, and Internet sites for academic libraries, selects as the "best in scholarly titles" approximately 10 percent of some 6,600 works reviewed each year.

Wolfgang Knauss, BS '58, PhD '63, the von Kármán Professor of Aeronautics and Applied Mechanics, has been elected an honorary member of the Society for Experimental Mechanics, as "an individual of widely recognized eminence in the field of experimental mechanics."

Yanshun Liu, a postdoctoral scholar in biochemistry and molecular biophysics, has been selected to receive a Damon Runyon postdoctoral fellowship, one of 20 awarded after a review by the scientific advisory committee of the Damon Runyon Cancer Research Foundation. The three-year fellowships are awarded to "outstanding young scientists conducting theoretical and experimental research that is relevant to the study of cancer."

Ares Rosakis, professor of aeronautics and mechanical engineering, has been selected to receive the 2003 M. M. Frocht Award, which is given annually by the Society for Experimental Mechanics Honors Committee to honor "outstanding achievement as an educator in the field of experimental mechanics." The award will be presented at the society's annual conference, which will take place this year June 2–4 in Charlotte, North Carolina.

Kip Thorne, BS '66, the Feynman Professor of Theoretical Physics, has been awarded the Robinson Prize in Cosmology by the University of Newcastle, England. He has also received the honorary degree of doctor of humane letters from Claremont Graduate University. □

Marie and John Goode

Alumnus Remembered with Professorship

John E. Goode, Jr., earned an MS degree from Caltech in 1941 and an Engineering degree in 1942, both in aeronautics. He spent most of his career with General Dynamics, where he rose to become vice president for systems technology, before retiring in 1976 to begin consulting for a number of aircraft manufacturers. "John lived and breathed the aircraft industry," according to his wife, Marie.

Goode attributed much of his success in the aircraft industry to his Caltech education (he had earned his BA in mathematics from the University of North Carolina). His particular expertise was in stability and control systems.

The Goodes joined the Provost's Circle of the Caltech Associates as life members in 1982 and the Torchbearers of Caltech in 1991. On that occasion, John wrote, "Caltech has meant a lot to me, and the least I can do is to remember it in my will."

The Goodes did indeed leave a bequest in their will to endow a professorship at Caltech. But when John died last year at the age of 83, Marie, who knew that endowing a chair at the Institute had long been a dream of his, decided that she wanted to move up the time-table and see that wish fulfilled now. The John E. Goode, Jr., Professorship will support a distinguished faculty member in aeronautical engineering.

"The history of aeronautics at Caltech is legendary, in part because of the passion and commitment of people like the Goodes," said Hans Hornung, the C. L. "Kelly" Johnson Professor of Aeronautics and director of the Graduate Aeronautical Laboratories at Caltech. "The Goode Professorship will be a boon for many, many years to the people and research efforts of GALCIT."

Said Richard Murray, chair of the Division of Engineering and Applied Science, "Named professorships are unique, highly visible ways to recognize outstanding faculty and provide a wonderful link for people who care about the Institute's past and future." □

John Goode (second from right) with the YB-60, Convair's alternative to the B-52. The YB-60 made its first flight in 1952.

For information contact:

Carolyn K. Swanson
Anne McMenamin
Gift and Estate Planning
California Institute of Technology
Mail Code 105-40
Pasadena, California 91125
phone: (626) 395-2927
fax: (626) 683-9891
planned_gifts@caltech.edu
www.gep.caltech.edu

Engineering & Science

California Institute of Technology
Pasadena, California 91125

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