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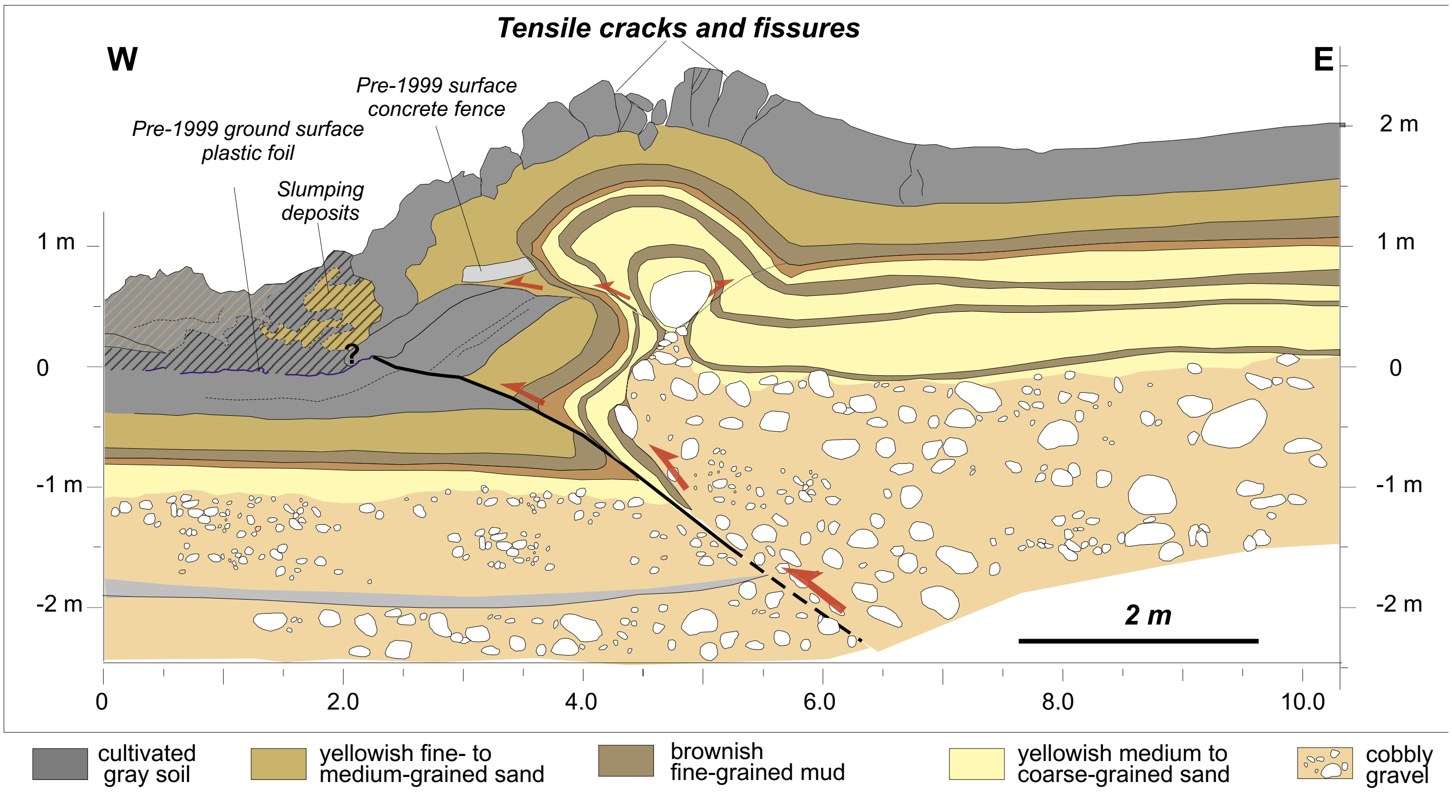
IN THIS ISSUE



Kerry Sieh and his colleagues dug this trench (on cover and at left) exposing the Chelungpu fault in Wufeng, Taiwan, a few months after the fault broke and produced the devastating earthquake of September 1999. At the fault, the earth was shortened a couple of meters and the right side rose more than a meter; the fault's motions are shown by the red arrows in the drawing above. The red fence in the background was a temporary replacement for a shattered concrete wall. The river gravel at the bottom of the trench shows that the area has also been subject to river floods—one more reason not to build there. See the story beginning on page 8. Cover photo and drawing courtesty of Jian-Cheng Lee of the Academia Sinica in Taiwan.

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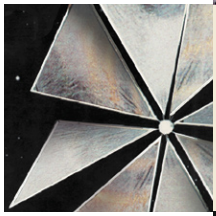

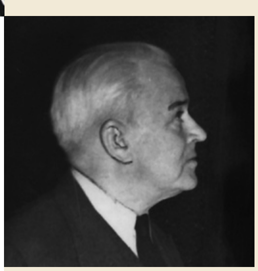

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Elachi (left) and Stone at the press conference.

The Lab Names One of Its Own

Charles Elachi (MS '69, PhD '71) has been named the new director of the Jet Propulsion Laboratory (JPL), which Caltech manages for NASA, effective May 1. President David Baltimore made the announcement at a press conference on January 31, where Elachi and Baltimore were joined by retiring JPL director Edward Stone, the Morrisroe Professor of Physics; and NASA administrator Daniel Goldin. Elachi has served in a variety of research and management positions at JPL since 1971. Most recently, he has been head of the Space and Earth Science Programs; other positions include manager for radar development and leader of the radar remote-sensing team.

Elachi "knows JPL better than anyone and will be best able to lead the Laboratory in the coming years," Baltimore said. "Charles has an extraordinary record of accomplishment in his 30 years at JPL. He is an alumnus of Caltech, and so knows the school well. He is an expert in remote sensing, and in recognition of his work, he was one of the youngest members ever elected to the National Academy of Engineering. He has long been a leader of planetary exploration at JPL and is widely respected at the Laboratory. I look forward to having a close working relationship with him."

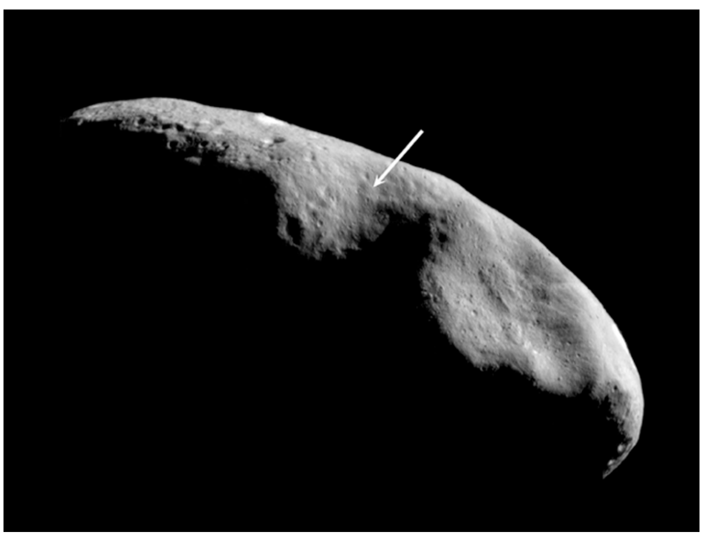
"Charles Elachi brings formidable talents to his new job, as both a scientist and a leader," said Goldin. "In addition to already being responsible for many of JPL's missions in solar system exploration, Earth sciences, and astrophysics, he has led efforts to create road maps of our exploration strategies decades into the future. He is both an effective administrator and a visionary."

Elachi said he was honored to be entrusted with the leadership of JPL. "For the last 40 years JPL has enjoyed a tradition of excellence as a NASA center and division of Caltech, and I intend to continue that tradition. My commitment is to continue the tradition of excellence and boldness in exploring our solar system, understanding the origin of galaxies, and applying that knowledge to better understand the changes on our own planet." The new post brings Elachi full circle, as he recalled being inspired as an 11-year-old in Lebanon by JPL's launching of Explorer 1—43 years ago to the day, he noted. "Maybe that's a good omen for me," he joked. He grew up to receive a BSc in physics from the University of Grenoble, France, and the Dipl.Ing. in engineering from the Polytechnic Institute, Grenoble, both in 1968, and then earned his Caltech MS and PhD in electrical engineering. He also earned an MBA from USC in 1978, and an MS in geology from UCLA in 1983.

Elachi is perhaps best known for his role in the development of a series of imaging radar systems for the Space Shuttle that have allowed scientists to see through the clouds that blanket Earth. (The technology also penetrates the top layer of soil in arid regions, revealing hints of what lies below.) He has participated in a number of archaeological expeditions in the Egyptian desert, the Arabian peninsula, and the Western Chinese desert, using satellite data to search for old trading routes and buried cities. Some of these expeditions have been featured in *National Geographic*, on PBS, and in *Caltech News* ("The Road to Ubar," April, 1992). He has also served as principal investigator on numerous NASA research and development studies and flight projects. He is currently the team leader of the Cassini Titan radar experiment and a coinvestigator on the Rosetta Comet Nucleus Sounder Experiment. He is the author of more than 200 publications on space and planetary exploration, Earth observation from space, active microwave remote sensing, wave propagation and scattering, electromagnetic theory, lasers, and integrated optics, and he holds several patents in those fields. He has written three textbooks on remote sensing and has taught EE/Ge 157, Introduction to the Physics of Remote Sensing, since 1982.

In 1988, the *Los Angeles Times* selected him as one of "Southern California's rising stars who will make a difference in L.A." In 1989, Asteroid 1982 SU was renamed 4116 Elachi in recognition of his contributions to planetary exploration.

Elachi is the second Caltech alumnus to be named director of JPL. The first, William Pickering (BS '32, PhD '36), headed the lab from 1954 to 1976. ☐—*JP*



On February 12, NEAR Shoemaker became the first spacecraft to land on an asteroid—all the more impressive when you consider that this legless orbiter was never designed to land on anything. NASA's Near Earth Asteroid Rendezvous mission, which was renamed in honor of the late Eugene Shoemaker (BS '47), the father of planetary geology, had been in close orbit around the 21-mile long Eros for a year. The craft touched down at a gentle four miles an hour and in an orientation that allowed its solar panels to continue to function, so jubilant scientists turned its gamma-ray spectrometer back on to get a close-up analysis of Eros's surface mineralogy. In this image mosaic, taken from an orbital altitude of 200 kilometers, the arrow points to the landing site. Gene's gotta be happy….

Sniff Me a Tune

When Hamlet told the courtiers they would eventually "nose out" the hidden corpse of Polonius, he was perhaps a better neurobiologist than he realized. According to research by Caltech neuroscientists, the brain creates subtle temporal codes to identify odors. Some neural signals change over the duration of a sniff, giving first a general notion of the type of odor, then a more subtle discrimination that leads to precise recognition of the smell. In the February 2 issue of the journal *Science*, Gilles Laurent, associate professor of biology and computation and neural systems, and postdoc Rainer W. Friedrich, now at the Max Planck Institute in Heidelberg, Germany, report that certain neurons respond to an odor through a complicated process that evolves over a brief period of time. These neurons, called mitral cells because they resemble miters—the pointed hats worn by bishops—are found by the thousands in the human olfactory bulb.

"We're interested in how ensembles of neurons encode sensory information," explains Laurent. "So we're less interested in where the relevant neurons lie, as revealed by brain mapping studies, than in the patterns of firing these neurons produce and in figuring out from these patterns how recognition, or decoding, works."

The researchers used zebra fish because these animals have comparatively few mitral cells and because much is already known about the types of odors that are behaviorally relevant to them. But the study likely applies to other animals, including humans, because the olfactory systems of most living creatures appear to follow the same basic principles. After placing electrodes in the brains of individual fishes, they were subjected to sequences of 16 odor components found in foods they normally seek. Analyzing the signals from the mitral cells showed that the information the fish could extract about a stimulus became more precise as time went by. The finding was surprising because the signals extracted from the receptor neurons located upstream of the mitral cells showed no such temporal evolution. "It looks as if the brain actively transforms static patterns into dynamic ones and in so doing, manages to amplify the subtle differences that are hard to perceive between static patterns," Laurent says.

"Music may provide a useful analogy. Imagine that the olfactory system is a chain of choruses—a receptor chorus, feeding onto a mitral-cell chorus, and so on—and that each odor causes the receptor chorus to produce a chord. Two similar odors evoke two very similar chords, making discrimination difficult. What the mitral-cell chorus does is to transform each chord it hears into a musical phrase, in such a way that the difference between these phrases becomes greater over time. In this way, odors that initially 'sounded' alike progressively become more easily identified."

In other words, when we

detect a citrus smell in a garden, for example, the odor is first conveyed by the receptors to the mitral cells. This initial firing allows for little more than the generic detection of the citrus nature of the smell. Within a few tenths of a second, however, new mitral cells are recruited, leading the pattern of activity to change rapidly. This quickly allows us to determine whether the citrus smell is actually a lemon or an orange.

However, the individual tuning of the mitral cells first stimulated by the citrus odor does not become more specific. Instead, the manner in which the firing patterns unfold through the lateral circuitry of the olfactory bulb is ultimately responsible for the fine discrimination of the odor. "Hence, as the system evolves, it loses information about the class of odors, but becomes able to convey information about precise identity," says Laurent. □—*RT*

The Ins and Outs of Over- and Undervotes

In December, following the contentious vote counting in the presidential election, Caltech and MIT decided to join forces to develop a voting system that will be easy to use, reliable, secure, and modestly priced. The project was the brainchild of the institutions' two presidents—Caltech's David Baltimore and MIT's Charles Vest—and, with $250,000 funding from the Carnegie Corporation, faculty from both campuses began collecting data and studying the range of voting methods across the nation.

Early in February, the Caltech/MIT Voting Technology Project submitted a preliminary report to the task force studying the election in Florida. Their nationwide study of voting machines offers further evidence supporting the task force's call to replace punch card voting in Florida. The statistical analysis also uncovered a more surprising finding: electronic voting, as currently implemented, has performed less well than was widely believed.

The report examines the effect of voting technologies on unmarked and/or spoiled ballots. Researchers from both universities are collaboratively studying five voting technologies: paper ballots with hand-marked votes, lever machines, punch cards, optical scanning devices, and direct-recording electronic devices (DREs), which are similar to automatic teller machines.

The study focuses on so-called "undervotes" and "overvotes," which are combined into a group of uncounted ballots called "residual votes." These include ballots with votes for more than one candidate, with no vote, or that are marked in a way that is uncountable.

Careful statistical analysis shows that there are systematic differences across technologies, and that paper ballots, optical scanning devices, and lever machines have significantly lower residual voting rates than punch-card systems and DREs. Overall, the residual voting rate for the first three systems averages about 2 percent, and for the last two systems averages about 3 percent.

This study is the most extensive analysis ever of the effects of voting technology on under- and overvotes. The study covers the entire country for all presidential elections since 1988, and examines variations at the county level. When the study is complete, it will encompass presidential elections going back to 1980, and will examine a finer breakdown of the different technologies, and a breakdown of residual votes into its two components: over- and undervotes. A final report will be released in June.

The analysis is complicated by the fact that voting systems vary from county to county and across time. When a system is switched, say from lever machines to DREs, the number of residual votes can go up due to voter unfamiliarity with the new technology.

"We don't want to give the impression that electronic systems are necessarily inaccurate, but there is much room for improvement," said Thomas Palfrey, Caltech professor of economics and political science.

"Electronic voting technology is in its infancy and seems the most likely one to benefit significantly from new innovations and increased voter familiarity," states the 13-page report.

Other Caltech members of the Voting Technology Project are Michael Alvarez, associate professor of political science, and Jehoshua Bruck, professor of computation and neural systems and electrical engineering. Participating from MIT are Stephen Ansolabehere, professor of political science, and Nicholas Negroponte, chairman of the Media Lab.

Check the web at www.vote.caltech.edu for further information, or see www.vote.caltech.edu/Reports/report1.pdf for the report itself. □—*JP*

Alan Alda is Richard Feynman in QED, a new play based on Tuva or Bust! and other Feynman tales. Fittingly, the world premiere is at the Mark Taper Forum, just down the Pasadena Freeway from Feynman's old haunts. It runs through May 13; tickets are available at www.TaperAhmanson.com or (213) 628-2772. On a recent visit to campus to soak up the atmosphere, Alda dined with president Baltimore and assorted campus luminaries.

The Jupiter Effect

In a study that strengthens the likelihood that solar systems like our own are still being formed, an international team of scientists has reported that three young stars in the sun's neighborhood have the raw materials necessary for the formation of Jupiter-sized planets. Data obtained from the European Space Agency's Infrared Space Observatory (ISO) indicate for the first time that molecular hydrogen is present in the debris disks around young nearby stars. The results are important because experts have long thought that primordial hydrogen—the central building block of gas giants such as Jupiter and Saturn—is no longer present in the sun's stellar vicinity in sufficient quantities to form new planets.

"We looked at only three stars, but the results could indicate that it's easier to make Jupiter-sized planets than previously thought," said Geoffrey Blake (PhD '86), professor of cosmochemistry and planetary sciences and professor of chemistry at Caltech and the corresponding author of the study, which made the cover of *Nature* on January 3. "There are over 100 candidate debris disks within about 200 light-years of the sun, and our work suggests that many of these systems may still be capable of making planets."

The abundance of Jupiter-sized planets is good news, though indirectly, in the search for extraterrestrial life. A gas giant such as Jupiter may not be particularly hospitable for the formation of life, but experts think the mere presence of such huge bodies in the outer reaches of a solar system protects smaller rocky planets like Earth from catastrophic comet and meteor impacts. A Jupiter-sized planet possesses a gravitational field sufficient to kick primordial debris into the farthest reaches of the solar system, as Jupiter has presumably done by sending perhaps billions of comets safely away from Earth into the Oort Cloud, which lies beyond the orbit of Pluto. If comets and meteors were not ejected by gas giants, Blake said, life on Earth (and any other Earth-like planets) could periodically be "sterilized" by impacts. "A comet the size of Hale-Bopp, for example, would vaporize much of Earth's oceans if it hit there. The impact from a 500-kilometer object—about ten times the size of Hale-Bopp—could create nearly 100 atmospheres of rock vapor, the heat from which can evaporate all of Earth's oceans."

The researchers did not directly detect any planets in the study, but nonetheless found that molecular hydrogen was abundant in all three disks. In the disk surrounding Beta Pictoris, a Southern Hemisphere star that formed about 20 million years ago approximately 60 light-years from Earth, the team found evidence that hydrogen is present in a quantity at least one-fifth the mass of Jupiter, or about four Neptune's worth of material. The debris around 49 Ceti, which lies near the celestial equator in the constellation Cetus, was found to contain hydrogen in a quantity at least 40 percent of the mass of Jupiter. Saturn's mass is just under a third that of Jupiter. 49 Ceti, which is about 10 million years old, is roughly 200 light-years from Earth. Best of all was a 10-million-year-old Southern Hemisphere star about 260 light-years away that goes by the rather unpoetic name HD135344. That star's debris disk was found to contain the equivalent of at least six Jupiter masses of molecular hydrogen.

The study also confirmed that planetary formation is not limited to a narrow "window" early in the life of a star, as previously thought. Because molecular hydrogen is quite difficult to detect from ground-based observatories, experts have relied on measurements of the more easily detectable carbon monoxide (CO) to model the gas dynamics of developing solar systems. But because the CO tends to dissipate quite rapidly early on, researchers assumed that the molecular hydrogen likewise vanished. This presumed lack of hydrogen limited the time in which Jupiter-sized planets could form. However, the new study, coupled with recent theoretical models, shows that CO is not a particularly good proxy for the total gas mass surrounding a new star.

Blake said the study opens new doors to the understanding of planetary growth processes around sun-like stars. He and his colleagues anticipate further progress when the Space Infrared Telescope Facility (SIRTF) and the Stratospheric Observatory for Infrared Astronomy (SOFIA) are launched in 2002. SIRTF, which will have its science headquarters at Caltech, alone could detect literally hundreds of stars that still contain enough primordial hydrogen in their debris disks to form Jupiter-sized planets.

The other authors are professor Ewine F. van Dishoeck and Wing-Fai Thi, the study's lead author, both of the Leiden University in the Netherlands; Jochen Horn and professor Eric Becklin, both of the UCLA Department of Physics and Astronomy; Anneila Sargent (MS '67, PhD '77), professor of astronomy at Caltech; Mario van den Ancker of the Harvard-Smithsonian Center for Astrophysics; and Antonella Natta of the Astrophysical Observatory of Arcetri in Florence, Italy. □—*RT*

Of Cell Phones, Memory Cells, and Flashy Nanocrystals

Scientists at Caltech and Agere Systems, formerly known as the Microelectronics Group of Lucent Technologies, have developed a technique that could result in a new generation of reliable nanoscale memory chips and smaller, less expensive cellular phones and digital cameras. Announced December 13 at the International Electron Devices Meeting, the work applies to so-called "flash" memory, which continues to store information even when the device is turned off. This information could include personal phone directories in a cellular phone or the pictures captured by a digital camera. A typical flash-memory chip stores 16 to 32 million bits of data, with each bit in a separate "cell." As chip sizes decrease, the cells become more difficult to make leakproof, and

¿Oye, CHICOS, Donde Está el Observatorio?

Los Angeles-area high school students will team up with Caltech researchers to study ultrahigh-energy cosmic rays on their own campuses, thanks to a recent grant from the Weingart Foundation, which donated $100,000 to establish the California HIgh school Cosmic-ray ObServatory (CHICOS) on four campuses in the Northridge area initially, expanding to at least 25 and possibly hundreds of sites eventually. Three of the four initial schools have a high number of students who are underrepresented in the sciences, which means the program may assist in increasing the number of future scientists in the United States. The schools are the Sherman Oaks Continuing Education School, and Sylmar, Van Nuys, and Harvard Westlake High Schools.

The research will be coordinated by Professor of Physics Robert McKeown. The program will also incorporate a high school teacher education component coordinated by Dr. Ryoichi Seki at California State University, Northridge. Teachers will develop curriculum materials to help their students participate in this research. Caltech will host a summer workshop where physics teachers and students can participate in the construction of new detector stations for deployment at additional sites.

The detector hardware, associated electronics, and computer equipment will form a networked system among the high schools. A large array of this type will enable the study of ultrahigh-energy cosmic rays through the detection of "showers," several kilometers in radius, of secondary particles the rays create in the Earth's atmosphere. These are the highest-energy particles ever observed in nature, and thus are of great current interest in the astrophysics and particle-physics community. Thus, while establishing a state-of-the-art experimental facility, this project will provide an exceptional educational experience for local high school students. When a majority of the 25 sites are operating, it is expected that the project will yield significant scientific results that will be reported in the scientific literature. □—*JP* stored data can be lost.

Using an aerosol technique developed at Caltech, silicon nanocrystals were sprayed through a bath of high-temperature oxygen to create memory cells comprised of silicon on the inside with a silicon dioxide outer shell. The silicon nanocrystals store the electrical charge, whereas the insulating silicon dioxide shell makes the cells leak-resistant. "As compared to conventional flash memories, these silicon nanocrystal memories offer higher performance, simpler fabrication processes, and greater promise for carrying memory miniaturization to its ultimate limit," said Harry Atwater, professor of applied physics and materials science, and project director. Atwater; Richard Flagan, the McCollum Professor of Chemical Engineering; postdoc Mark Brongersma; grad students Elizabeth Boer (MS '96), Julie Casperson, and Michele Ostraat (MS '98); and Jan de Blauwe and Martin Green at Agere Systems developed a method to break up each cell into 20,000 to 40,000 smaller cells. Therefore, even if several of the smaller cells spring a leak, the vast majority of the charge will not be lost and the bit of data stored in the whole memory cell will be retained.

The aerosol approach has several advantages over the conventional lithographic techniques used to make today's flash memory cells. Because it requires fewer steps, it is less expensive and the chips take less time to produce. In addition, the aerosol approach will allow researchers to continue making smaller and smaller devices. The cells are also extremely robust—one cell has gone through a million charge-discharge cycles without significant degradation, whereas 10,000 cycles is considered satisfactory for a traditional chip. The research was supported by the National Science Foundation and NASA. □—*RT*

Caltech scored first, Caltech scored last, but That Other Institute of Technology scored more often in their first ever women's basketball matchup in front of a packed house in Braun Gym on January 5. Final score: CIT 46, MIT 80.

In Search of the Mind's Eye

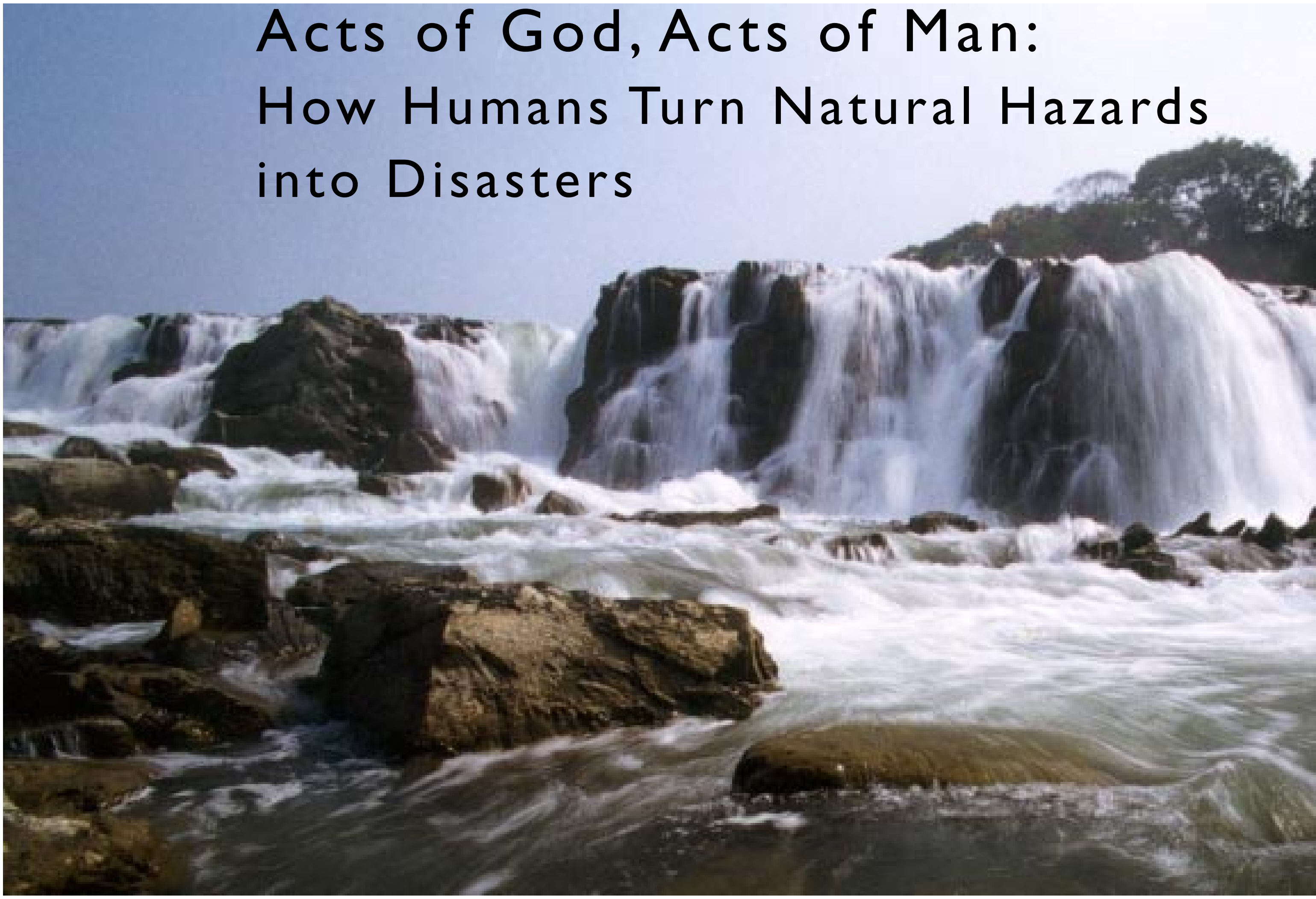
A study of patients awaiting brain surgery has shown that humans use the same neurons to conjure up mental images that they use when they actually see the real object. In the November 16 issue of *Nature*, UCLA neurosurgeon and neuroscientist Itzhak Fried and Caltech neuroscientists Christof Koch, professor of computation and neural systems, and grad student Gabriel Kreiman report on results obtained by questioning nine patients who had been fitted with brain sensors. The patients, all suffering from severe epilepsy uncontrolled with drugs, were being observed for a period of one to two weeks so that the regions of their brains responsible for their seizures could be identified and later surgically removed.

During their extended hospital stay, the patients were asked to look at photos of famous people, pictures of animals, abstract drawings, and other images. While they were looking at the images, the researchers noted the precise neurons that were active. Then, the subjects were instructed to close their eyes and vividly imagine the images. Again, the researchers noted which neurons were active. It turns out that a subset of neurons in the hippocampus, amygdala, entorhinal cortex, and parahippocampal gyrus would fire when the patient looked at the image and also when he or she imagined the image.

The results build upon work by Fried's group showing that single neurons in the human brain are involved in memory and can respond selectively to a wide variety of visual stimuli as well as stimulus features such as facial expression and gender. According to Koch, the study helps settle long-standing questions about the nature of human imagery. Particularly, the research sheds light on the process at work when humans see things with the mind's eye. "If you try to recall how many sunflowers there are in the Van Gogh painting, there is something that goes on in your head that gives rise to this visual image," Koch says. "There has been an ongoing debate about whether the brain areas involved in perception during 'vision with your eyes' are the same ones used during visual imagery."

The problem has been difficult to address because the techniques that yield very precise results in animals are generally not suitable for humans, and because the brain imaging techniques suitable for humans are not very precise, Koch says. Such techniques can image only large portions of the brain, each containing on the order of one million very diverse nerve cells. "Recording the activity of single cells allows us to investigate the neuronal correlates of visual awareness at a detailed level of temporal and spatial resolution," says Kreiman. The work was supported by the National Institutes of Health, the National Science Foundation, and the Center for Consciousness Studies at the University of Arizona. □—*RT*

Acts of God, Acts of Man: How Humans Turn Natural Hazards into Disasters



by Kerry Sieh

Geologists have a particular appreciation of Earth's beauty. That's not to say that those of you who are not geologists don't appreciate it. We would probably all agree that the waterfall above is a beautiful thing. But some of the same things that make Earth beautiful also make it dangerous, and to some degree it's the danger in the beauty that attracts the geologist. I'm going to discuss the hazardous side, and I'm going to argue for a different approach to handling the natural hazards that this beautiful Earth puts beneath our feet.

In the 20th century, and in fact in the first and second millennia, we just reacted to natural disasters. We basically cleaned up after they happened and continued on as before, leaving our great-grandchildren to suffer the same fate, next time around. Now, at the turn of the century, the turn of the millennium, I suggest we start looking at hazards differently than we have looked at them in the past. Let's understand them as the geologist or the earth scientist does, so that they don't destroy our cities, homes, and lives. Let's actively reduce our exposure to hazards, rather than being just reactive to them.

The dramatic increase in human population over the past several decades has resulted in an enormous increase in the actual dollar losses and in the loss of human life associated with natural disasters. You see the same basic trend with earthquakes, with landslides, with tsunamis, with almost every hazard—an almost exponential increase over the last couple of decades. This trend will most likely continue if we don't change the way we act with respect to our planet's behavior.

Worldwide, about 200 cities with a population of more than 500,000 lie within 100 kilometers of known active faults; Los Angeles is one such city, as are San Francisco, Wellington (New Zealand), and Taipei (Taiwan). Ahmedabad (India) and San Salvador only recently suffered large earthquakes. Central America, the Mediterranean countries, the Middle East, and large parts of Asia are particularly susceptible to earthquake damage. But we associate very few of these 200 cities with earthquake hazards, because the Earth's metabolism is so much slower than ours that most of them have not been devastated by an earthquake in living memory. We think in terms of years or months,

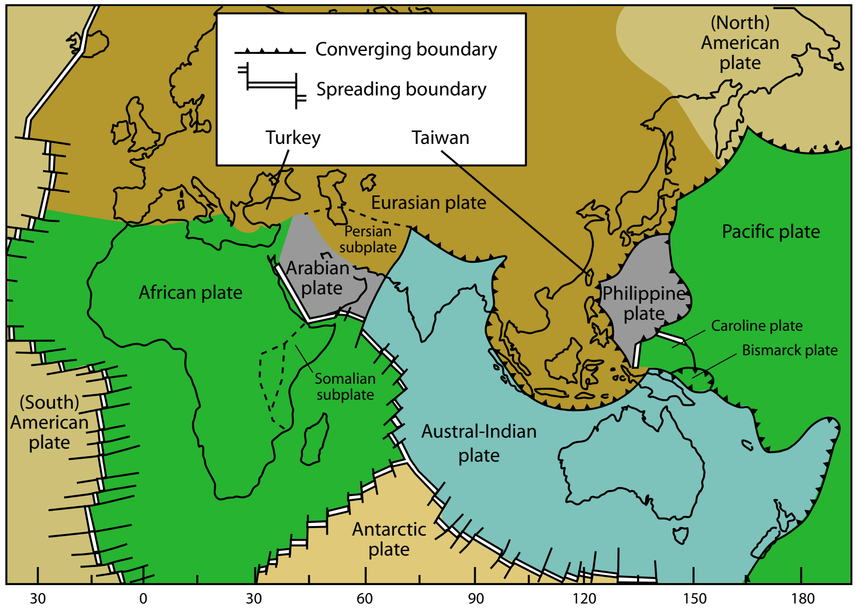
Photo by Sheng-Tao Kuo

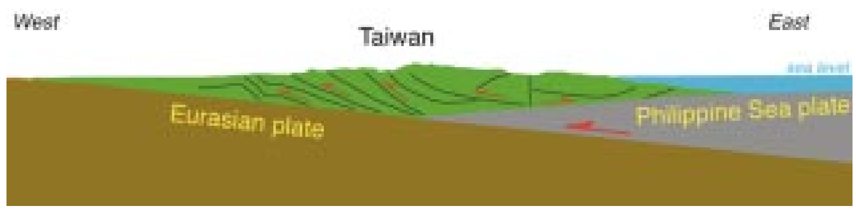
This is a tale of two countries, Taiwan and Turkey, and the devastating earthquakes that hit them in 1999. When I look at the waterfall on Taiwan's Tachia River, I'm reminded of one of the reasons why I became a geologist: to understand why this big escarpment rose in the middle of this river is a joy and a delight.

not decades or centuries. We teach our kids not to cross the street without looking both ways, but we don't teach them to worry about something that might happen in 50, or 100, or 500 years. Of the earthquakes that we've heard about in the last decade, none has a recurrence interval of less than about a thousand years, with the exception of the Turkish earthquake that I'll be discussing. This low metabolic rate inures us to the fact that the faults are there, that earthquakes happen. Generations come and go, thinking they are perfectly safe, when in fact they are living on a time bomb with a very long fuse.

This is a tale of two countries, Taiwan and Turkey, and the devastating earthquakes that hit them in 1999. When I look at the waterfall on Taiwan's Tachia River above, I'm reminded of one of the reasons why I became a geologist: to understand why this big escarpment rose in the middle of this river is a joy and delight. But if I were an engineer, looking at what happened to my bridge (right), my feelings would be very different. I'd be very upset. Before the earthquake, the geologist could have told the engineer: "You really

The fault scarp, about seven meters high, could be seen clearly from the air, even without a broken bridge for emphasis. The earthquake's lesson, however, was not learned; see page 13. (Photo provided by Jack, Yung-Wan Lien, Flying Tiger Photographic, Inc.)





Taiwan sits on the boundary of the large Eurasian plate and the Philippine Sea plate (above). As they converge, the Philippine Sea plate rides up over the larger plate (right), crunching up the shallow marine sediments into a mountainous island (far right). Note also in the map above the collision of the Arabian plate with the Eurasian plate, which has made Turkey subject to earthquakes.

shouldn't put your bridge abutment here because there's a big fault under it. And when that fault moves, it moves with many meters of slip, and you're going to lose that $10 million bridge." But the engineer, as is typical, didn't talk to the geologist until after the earthquake. And we'll see that, even then, the engineer wasn't encouraged to rebuild with any accommodation for future fault ruptures.

Taiwan spans the boundary between a small plate called the Philippine Sea plate and the great Eurasian plate, which runs all the way from the middle of the Atlantic and Iceland eastward to Japan. Taiwan used to be sediment sitting in the shallows of the continental shelf on the edge of the Eurasian plate. When the continental margin of the bigger plate started getting jammed down the subduction zone that separates the two plates, the Philippine Sea plate began to ride up over the continental shelf, doubling up the sediments between thrust faults to create the 300-kilometer-long island that we see today. Not all of these faults are active now, but the one that moved to produce the 1999 earthquake obviously is. The mountainous mass along the eastern side of the island has risen in just a geological twinkling of an eye—4 million years or so. It's starting to go back down again in the north, near Taipei, but it's still rising up in the central reach of the island and is just getting started in the south—the rate of uplift in some places is nearly a centimeter per year.

The fault that broke on September 21, 1999, the Chelungpu fault, runs along the western edge of the mountain front in the center of the island. A well-known Princeton geologist, John Suppe, determined its geometry in the early 1980s, using borings and seismic reflection data collected for oil exploration. The pictures on the opposite page give some idea of the damage the fault rupture wrought. One side of the fault rode up and over the other, forming an escarpment several meters high; fields that once were flat are now three or four meters higher on one side than on the other; buildings and bridges across the fault were wrecked.

Now, fields and rice paddies can be regraded. Those are perfectly good things to have on a fault, but cemeteries are a different matter. The Taiwanese have great reverence for their ancestors, and it was of great concern that many graveyards were ripped asunder by this earthquake. It's a serious matter that they will have to consider in making new zoning laws after this earthquake.

Buildings don't behave very well if they straddle fault ruptures, either. Most didn't actually collapse, though playing billiards in some of them would be a bit difficult now. Buildings very close to the fault but not directly on it commonly survived intact and are still habitable, but buildings right on the rupture did not fare so well. One estimate is that 35 to 50 percent of the building damage was due to ground deformation under foot. The fault came up so fast in one building that, on the hanging-wall block (the rising side of the fault), the first story simply collapsed, but it was left intact on the foot-wall block (the lower side). The entire scarp formed in a matter of about two seconds. One guy on the first floor of a building woke up, opened his door, and looked right into his neighbor's second-floor window, which used to be across the street.

This earthquake was very important because it showed that the engineering problem has been basically solved. The Taiwanese know how to build buildings that don't collapse, even during some of the heaviest shaking imaginable. Well-engineered buildings didn't fail at all. Some improperly built structures collapsed, and many people died, but the point is that we know basically how to build buildings to survive earthquake shaking.

But the improper use of land is a problem we have barely begun to tackle—land use with respect to faulting, with respect to hazards from floods, landslides, tsunamis, slumping into the ocean, and so on. Let's go back to the beautiful waterfall on the first page and the bridge across the river. When it failed, people wondered why. Well, it's really quite simple: the bridge was built across the fault. The waterfall is the fault scarp, and when one side moved up and over the other side, the bridge fell off its abutments. A large dam upstream was also partially destroyed by the fault rupture. The main portion of the dam rose nine meters over the left abutment. How fortunate that the dam didn't fail catastrophically and kill thousands of people downstream.

So, if you lived in central Taiwan and were building a bridge or a dam, would you prefer hiring a geological consulting company to investigate possible problems? Or would you favor saving the few hundred thousand dollars in consulting fees, and gambling that nothing would happen? To me the answer is obvious, but, of course, as a geologist I'm biased toward the longer view.

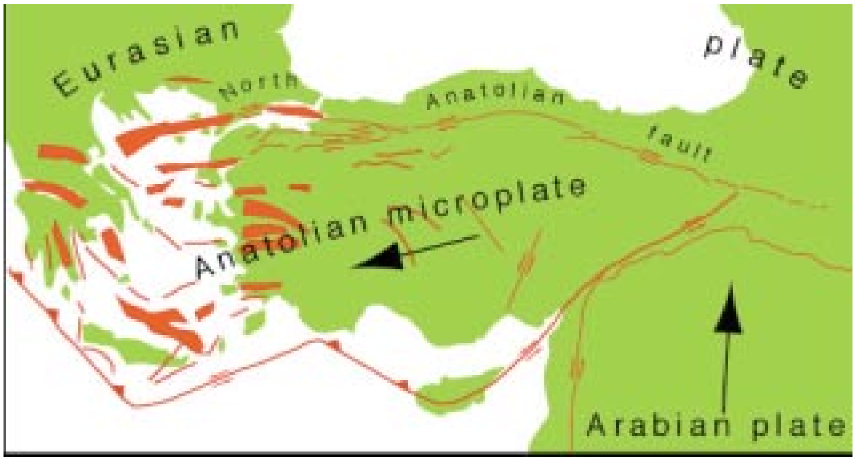
At left above is a shaded-relief map made from topographic mapping at 40-meter postings. It's similar to data that will be produced from the Shuttle Radar Topography Mission (SRTM), which NASA flew early in 2000. This latest mission will be giving us topography between 60 degrees north and 60 degrees south at about 30-meter postings. Now, if the National Mapping Agency agrees to release to us civilians the 30-meter data, we're going to have a fantastic time mapping many of Earth's geologic hazards. It will be much easier to map faults *before* they break, and then use the maps for land-use planning. I got the shaded-relief map from one of my Taiwanese colleagues just before I went to Taiwan half a year after the earthquake, and I thought I'd practice with it, to see how useful the high-resolution SRTM data might be. I mapped the fault just from this map, before I ever looked at the map of the ruptures that were produced after the earthquake. I mapped about 80 percent of it correctly within the 40-meter resolution of the map, including many of the little secondary faults.

During the Chi-Chi earthquake, as it was named, the Chelungpu fault broke from stem to stern. It was a beautifully behaved thrust-faulting event. It may well be a good analogy to what will happen when our own Sierra Madre fault ruptures and the San Gabriel Mountains fling themselves out toward the foothill communities, from San Fernando, through Pasadena, to Upland. Paleoseismic data collected to date suggest that our fault also slips in large events, about five meters each, along its entire 60-kilometer length. We don't yet know exactly how often this fault breaks, but we're working on that. But its recurrence interval is probably measured in thousands of years rather than hundreds.

The mountains of Taiwan's Central Range, which rise steeply east of the Chelungpu rupture, are very rugged and extremely steep. They have been rising for about the same period of time as the San Gabriel Mountains—three or four million years. But they have risen many times faster—several millimeters per year. During the 1999 earthquake, massive landslides rolled down into many of the mountain valleys and caused spectacular damage. Of the people caught up in this myriad of seismically induced landslides, very few survived (in all, more than 2,000 people died in this earthquake). In the case of the biggest slide, some survivors rode the slide about a kilometer and a half down. The Chi-Chi earthquake shows us, once again, that seismically induced landslides

Rupture of the Chelungpu fault produced the 1999 earthquake; the fault is marked by the red line in the shaded-relief map above. Some of the damage from the fault rupture can be seen below: part of what was formerly a flat field rose up four meters (left); buildings tilted, and bridges were ripped apart. More than 2,000 died in the quake.

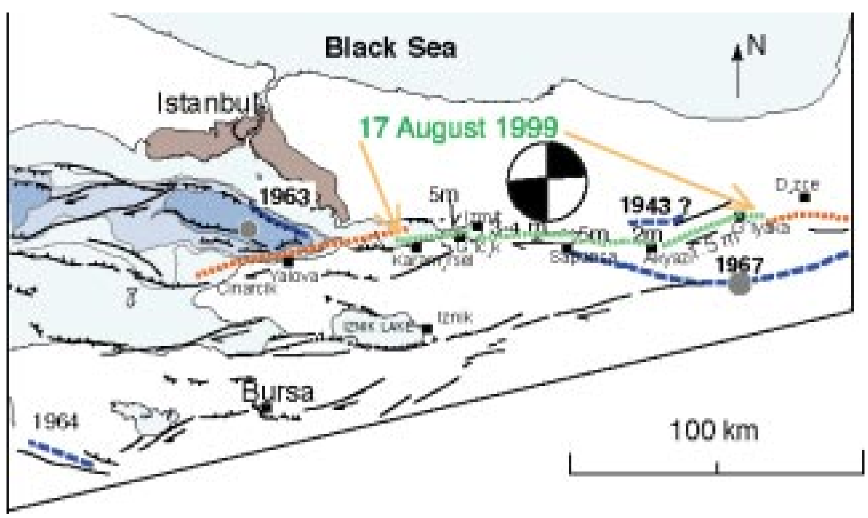
Photo provided by Jack, Yung-Wan Lien, Flying Tiger Photographic, Inc.



The collision of the Arabian plate (above) with the Eurasian plate is squeezing Turkey westward, creating the 2,000-kilometer-long North Anatolian fault, numerous segments of which have broken in the past 60 years. The last segment, closest to Istanbul, has yet to break. The four segments that ruptured on August 17, 1999 are shown in green at right. The red section near Düzce ruptured just three months later, on November 12.

can be a very significant hazard. From the experience in Taiwan, I would caution against dense development within our own precipitous San Gabriels and encourage our policy makers to seek geological advice before issuing permits.

The Taiwanese fault moved primarily vertically. Now, let's go to Turkey and look at a fault that moved horizontally, more like our San Andreas fault. The North Anatolian fault is the indirect result of the ongoing collision of the Arabian plate and the Eurasian plate, which is causing Saudi Arabia and the Persian Gulf to slide under Iran. This contraction of the Earth's surface is squeezing Turkey westward toward Greece and Libya. The fault, which runs nearly 2,000 kilometers from the Kurdish part of Turkey past Istanbul, is the northern margin of this extruding block.



Many sections of the North Anatolian fault have broken in the past 60 years. An extraordinary westward progression of earthquakes in 1939, 1942, 1943, 1944, 1957, and 1967 pointed right toward the place where the earthquake happened on August 17, 1999. Several published papers had made this long-term forecast. The only sections left to break in this remarkable sequence are those that constitute the 300-kilometer portions closest to Istanbul. Unfortunately, this seismic gap lies predominantly under water, so direct access for geological investigation is impossible. People in Istanbul are quite concerned about this forecast, with good reason, but nonetheless, Istanbul's population is growing by something like 100,000 a year, as people come in from the countryside in search of a better life. Many of them live in hastily erected buildings at the city's edges.

The North Anatolian fault is similar to the San Andreas only in that it moves horizontally; otherwise it's quite different, particularly in its segmentation. Four major segments broke in 1999. We don't have such segments on the San Andreas. The San Andreas is very smooth, which may well be why it produces earthquake ruptures several hundred kilometers long and magnitudes in the upper 7s. Turkey gets mostly 7.5s and less, because the segmentation seems to stop or at least impede the rupture from growing longer than a hundred kilometers or so. In the 1999 earthquake, four segments with a combined length of about 110 kilometers broke in a single magnitude 7.4 event. Tens of thousands died. Right after the August earthquake, my Turkish colleague, Aykut Barka, noted that a short neighboring segment, just to the east, near Düzce, was the only remaining segment between the new break and eastern Turkey that had not yet ruptured. He warned that it might well be the next to go. Sure enough, less than three months later it too broke, with about four meters of slip, causing a magnitude 7.1 earthquake.

Although the fault zone isn't paper-thin, it's fairly narrow—only a few meters wide. Everything right on top of the fault was completely destroyed, but you didn't have to be right on the fault to sustain great damage. A resort hotel built on loose, saturated sediments on the shore of Lake Sapanca is now swamped. The swimming pool tips into the lake, and the beautiful little cabanas are much wetter than they were ever intended to be. The hotel itself looks in relatively good shape, but if you should step up to the bar, you'll find that the bar rail is a foot under water. The sediments are so young and unconsolidated that



The resort hotel on Lake Sapanca (above left) was not heavily damaged, but when earthquake shaking caused the shallow sediments on which it was built to compact, the land slumped and the lake waters rose up over the swimming pool (and into the first floor, as well). The photo at far right, above, of Gölcük shows that it can be a costly mistake to build so close to a shoreline. Many apartment buildings suddenly slumped into the sea atop a small landslide. The new coastline in the photo is several buildings farther inland than before the earthquake.

the ground shaking caused them to compact; and when the sediments compacted, the sea rolled in 100 meters or so. The ancient record tells us that young sediments in such settings are notoriously good slumpers. So you're well advised not to build in such places. A parkway or a golf course would be just fine there, but it's best not to build a major metropolitan region right up to the shoreline. It's just asking for trouble.

In the town of Gölcük, close to the epicenter, the old waterfront is now 150 to 200 meters out in the water. People who lived near the waterfront suddenly found themselves sleeping beneath 40 meters of water; many hundreds of people and many millions of dollars were submerged beneath the waves.

When the World Bank, along with several other agencies, made a loan of about $1.7 billion to the Turkish government for rebuilding, their first requirement was that a mitigation study be done first. They said, "Before you do anything to rebuild anything anywhere, do the hazard study first to tell you where to put your new buildings and where not to put them." It's a step in the right direction, but it remains to be seen whether or not Turkey will use the loan effectively.

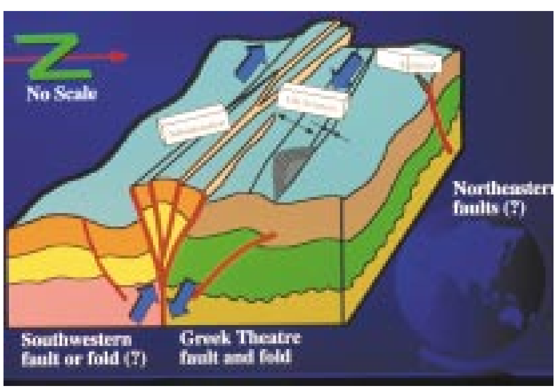
What can we do better, or at least differently, in the third millennium to reduce our exposure to these natural hazards? I haven't given you the entire spectrum of geological disasters, but I've given you a taste of a few of them: landslides, fault rupture, slumping, submergence of young sediments. But of course, there are others—tsunamis, and even asteroid impacts, for example. We can't really do much about the latter, which are fortunately exceedingly rare, but we can do something about the others.

What can we do about the hazard of fault rupture? When I visited Taiwan, six months after the earthquake, I found that in many places the houses that had been torn in half along the fault had been hauled away, and that new structures were being built in the same place. These new structures will probably be just fine, at least for 100, 200, maybe even 300 years. But when the next earthquake rupture occurs, property will once again be destroyed, and people may well perish.

This construction is happening before the government has enacted regulations to guide rebuilding. Remember the photo of the bridge at the beginning of this article? The photo below shows what's left of it; and it shows an excavator digging a deep pit where one of the supporting

Another mistake can be seen here (right): the same bridge seen on page 9, a few months later being rebuilt in exactly the same place—right on the fault.

San Bernardino Valley College (right) sits astride the San Jacinto fault, which runs directly through the administration building (the vertical blue rectangle to the left), the library (next to it in blue and gold), the campus center (the purple square below it), and the life sciences building (also blue). Other buildings, such as the Greek theater and the auditorium (top, green) are not right on the fault but could be damaged by folding. A schematic drawing of the fault zone is shown below: buildings on the fold will experience vertical motion in an earthquake, while strike-slip motion will affect those along the fault.



pillars used to be. According to Clarence Allen, professor of geology and geophysics, emeritus, who was there less than a month after I took the photo, this excavation for the new support pillar had been dug through the fault plane, from the hanging wall into the foot-wall block, and the fault separating young gravels underneath from the bedrock above had been beautifully exposed. If the bridge lasts more than a few hundred years, it will be there when the fault breaks again, and somebody is going to have to spend millions of dollars to rebuild it once more. What is the rationale, I wonder, for not rerouting the road now and crossing the fault at a point where it can be done with a less expensive roadbed rather than with a bridge?

Let's turn now to Southern California, where we have our own share of earthquake hazards. We can take a holier-than-thou attitude and claim that we do things right here, but that's not as true as we'd like to believe. Nevertheless, let's take a look at one example of a long-range vision of hazard mitigation. A few years ago we did a little study of the San Jacinto fault, a major fault that runs through Colton and San Bernardino. In fact, it runs right through San Bernardino Valley College. I live up in Lake Arrowhead, and a lot of my kids' friends go to Valley College after high school. It has a beautiful auditorium, one of the nicest Spanish-colonial-style buildings in Southern California. They built the campus there to avoid the hazard of flooding, because the location is up on a little ridge—the fault zone, it turns out. So they were smart about flood hazard, but not about earthquake hazard—out of the frying pan and into the fire.

Back in 1935, after the Long Beach earthquake, Valley College hired John Buwalda, the first geologist here at Caltech, to come out and see if they had any problems with regard to earthquakes. And he said, "Oh, my gosh; you've got a big fault going through the campus." In fact, he recommended a thousand-foot-wide zone of no building, which basically took in almost the entire campus. They ignored his advice, even though they paid for his report. A few years ago, the trustees called me (Buwalda's been gone a long time) and asked what they should do. They wanted to have a long-term master plan, a 30-, 40-, 50-year master plan for development. And they knew they had a fault problem.

We went out and dug a series of trenches during their winter break. We actually pinpointed where the fault traces are, where they've been moving for 10,000 years or longer. We located where there was deformation going on—tilting and anticlines and so on. In one of the trenches, we found a fold over a blind thrust, about three meters high. The Hollywood fault is doing the same thing near the Capitol Records building, but with a scarp about 15 meters (50 feet) high. And if you could look deep under the Library Tower building in downtown Los Angeles, you'd see the blind-thrust fault there. At the surface it shows up as a big escarpment. At Valley College one little blind-thrust fault is about five meters down, deforming older 10,000-year-old sediments and not deforming the very youngest ones, which are mainly fill containing concrete blocks and bricks. When we locate a fault like this, we can actually see how it's deforming the ground. And we can determine what sort of deformation a building will experience, whether it's vertical or strike-slip.

We can make a map showing precisely, within a foot, where the fault lies. In the main zone, we would expect to have anywhere from a meter to five meters or so of horizontal motion when the San Jacinto fault breaks again. We gave Valley College a 100-year earthquake scenario and a 400-year scenario, and told them they had to worry about folding as well as faulting. When the fault breaks, the administration building is going to get ripped in half, as well as the library built in the early '70s; the life sciences building is also in trouble. The campus center, built in 1970, is right squarely on the fault; the auditorium I like so much is off the fault but on the fold.

This went to the state architect, who spent two or three years figuring out what the college should do in terms of retrofits, building removal and demolition, new building construction, and so on. Then Congressman Jerry Lewis (R-San Bernardino) managed to get $34 million for the community college district, which is going to rebuild. The college is going to remove all the buildings from the fault zone and put replacements else-

A new layout for San Bernardino Valley College moves all buildings off the fault zone and orients them parallel to the long axis of the fault.

In Gölcük, Turkey, a partially built automobile factory sustained the greatest damage—more than two meters of vertical motion—in its body shop (right, below), which was visibly evident in the body shop's sunken pillars (right, above). When rebuilding after the quake, the owners, on the advice of geologists, moved the body shop to higher ground, farther from the fault.

where. And the long axis of the buildings will be oriented parallel to the fault, so that, just in case the geologists didn't find everything, the buildings will present less of a cross section to be hit by the fault. The college is doing a really responsible thing. For those of us who deal with these tragedies time and time again, it's gratifying to see someone caring about their children and great-grandchildren.

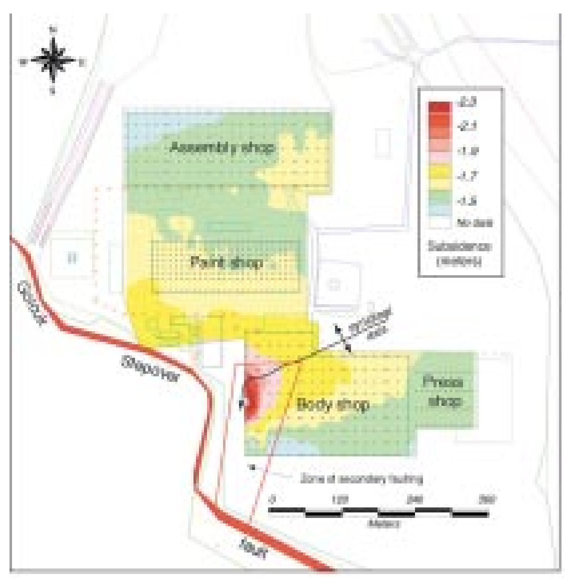
San Bernardino Valley College is a model for how the whole world might behave in the third millennium. What about Taiwan? With the information we already have, it is eminently possible to make a very detailed map of the active faulting and folding in Taiwan. Once that's done, I hope in the next couple of years, someone wanting to locate, say, a new chip-manufacturing plant could look at what the seismic or other geotechnical hazards are. If there are problems, they still have some choices at that early stage. Probably they would choose to put the plant a long way away from an active fault. Or, if they don't have that choice, a seismologist can calculate "synthetic" seismograms for the potential earthquake on that fault to estimate likely ground motions, which can be taken into account in the design. I chose this as an example, because chip prices increased twofold after this last earthquake, due, I'm told, not to damage to the buildings, but to damage to the actual manufacturing equipment inside the plants.

One smart thing to put along a fault is a park, and the Taiwanese are preserving parkland along this fault as a monument. If this were Japan, of course, they would preserve 50 kilometers' worth of park and create a $50 million museum—this is what they've done along the 1995 fault rupture near Kobe!

What needs to be done about the slumping and subsidence hazard? Going back to Turkey, an American-Turkish automotive company was building an assembly complex of four large buildings near Gölcük, very near the fault and just on the coast. The company is putting half a billion dollars into the construction of this plant, and the earthquake happened about $50 million into it. Fortunately, only a small piece of the fault zone hit the buildings directly, but unfortunately, there was also a lot of warping; the buildings hadn't been set back far enough from the fault.

The body shop, the building closest to the fault, provided us with some information about what occurred during the earthquake. The building's pillars, spaced about 10 to 15 meters apart, had been surveyed before the earthquake, and knowing their elevations to the nearest millimeter allowed us to reconstruct the folding. (When we first saw what had happened to the pillars during the earthquake, we thought it was just fantastic, which caused our clients to look at us a bit funny, wondering just what sort of consultants they had hired.) Along the fault plane, the vertical dislocation was 1.5 to 2.4 meters. And where you had the highest vertical slip, you also had the highest amount of subsidence. The pits down in the floor of this building were actually under water after the earthquake. Having put $50 million into this already, these guys came to us and asked if they should just abandon the site. The government had given them the land; the geologist they had talked to had said there were no problems, but one more earthquake like this and they're under water. They asked us when this is likely to happen again.

So, should we tell these guys to move or should we tell them to stay? Let's look at the history. In 1509, there was a big earthquake, and we think that it was produced by the rupture of most of the segments of the North Anatolian fault near the



The image at left was created by draping Landsat data over a Shuttle Radar Topography Mission map of Pasadena and the San Gabriel Mountains. The Sierra Madre fault, very similar to the Chelungpu fault, runs along their base, right through JPL, at center left. The Rose Bowl in the Arroyo Seco can be seen at lower left.

A cross section through the Sierra Madre fault (from the north end of Lincoln Boulevard) shows two sedimentary deposits (blue and pink) that are evidence for large fault ruptures in the last 15,000 years.

site. It was the most destructive earthquake in Istanbul in the last thousand years. In 1719 another earthquake occurred with, we think, almost the same rupture pattern as in 1999. In 1766, there was an earthquake in May that damaged Istanbul, and later that year another one damaged the Gallipoli Peninsula. So there was this cluster in the 1700s —bang, bang, bang, all in a matter of about 50 years. Could this happen again and mess up this plant if it's sitting right here? The answer is almost certainly not, because it looks as if these earthquake clusters have about 230-year intervals—almost like clockwork. In our report, we said to the automotive company: "Don't worry about the main fault; worry about adjacent earthquakes shaking your facility and about minor, secondary faulting on your site. If you really can afford a longer vision, don't build here at all, because it's going to submerge in two or three centuries, and somebody will have to deal with the problem then." They decided to deconstruct the entire 200-meter by 100-meter body shop and build it higher on the site and away from the secondary faulting so that when submergence occurs, they'll at least have the body shop. They're doing the right thing for a 100-year vision, but not for the 250-year vision that we had encouraged. They took a middle road toward mitigation, because they wanted to be making cars for the local market within a year of the earthquake. But they are consciously leaving much of the problem to a future generation.

What about landslides and liquefaction? Geologists can tell you where these will occur. We can see it in the prehistoric record; we can see it in the geotechnical details of the soil; and we can see it close to home. In the SRTM image at left (with Landsat imagery draped over it) of Pasadena and the San Gabriel Mountains, you can see the Arroyo Seco at lower left. You can see the Jet Propulsion Laboratory up at the top of the arroyo (it has a big fault running right through the administration building). At left is a trench we dug at Alta Loma Park at the north end of Lincoln Boulevard, exposing the fault. It shows that there have been two five-meter displacements in the last 15,000 years, where the mountains have shoved up over Altadena. They're very rare events, only about every 7,000 or 8,000 years. But the last one was about 8,000 years ago, so the next one could well happen within the next few centuries.

The California Division of Mines and Geology has provided hazard maps for much of the urban part of the state. The maps were mandated after the 1989 Loma Prieta earthquake in Northern California. These maps show liquefaction to be a potential hazard in the Arroyo Seco, but nowhere else in Pasadena. Landsliding and rock falls are shown to be a problem in parts of the Verdugo Hills and large parts of the San Gabriels. City planners are now wondering what to do with this information. Should we be worrying about these things? We have to worry about them now, because if something happens and we already had the maps from the state and we did nothing, we're

We have a clear choice: we can live with our beautiful, dangerous Earth as we have in past millenia, or we can learn where to put our bridges, campuses, houses, and factories to minimize the destruction.

going to get our socks sued off. So we want to act responsibly. Municipalities in California are now dealing with this problem. Turkish and Taiwanese municipalities need first to develop the infrastructure just to *begin* to deal with these sorts of problems.

Geologists can map volcanic, flood, and tsunami hazards very effectively, but there are some hazards we probably have to ignore—immense, catastrophic volcanic eruptions, for example, hundreds of times more voluminous and extensive than the eruption of Mount St. Helens. The valley downslope from Mammoth Mountain blew up 700,000 years ago and covered most of the western United States with ash. Yellowstone has gone up twice in the last million years. But these are very infrequent events; we'd probably better just duck and cover. Pieces of Hawaii go sliding off into the ocean every once in a while, producing tsunamis that are on the order of 350 meters high. I don't think we can design around those or plan for them. There was a large runout landslide in the Mojave 17,000 years ago, off the northern flank of the San Bernardino Mountains; this *could* happen to San Bernardino on the urban side of the mountains, but I guess we have to cross our fingers and hope that doesn't happen. I don't see any way to rationally plan for such an immense catastrophe.

PICTURE CREDITS:
10 — Doug Cummings; 10, 11 — C. T. Lee; 11, 13, 15, 17 — Kerry Sieh; 12-13 – Aykut Barka; 13 — Timothy Dawson; 14-15 — Earth Consultants International; 16 — NASA, Charles Rubin

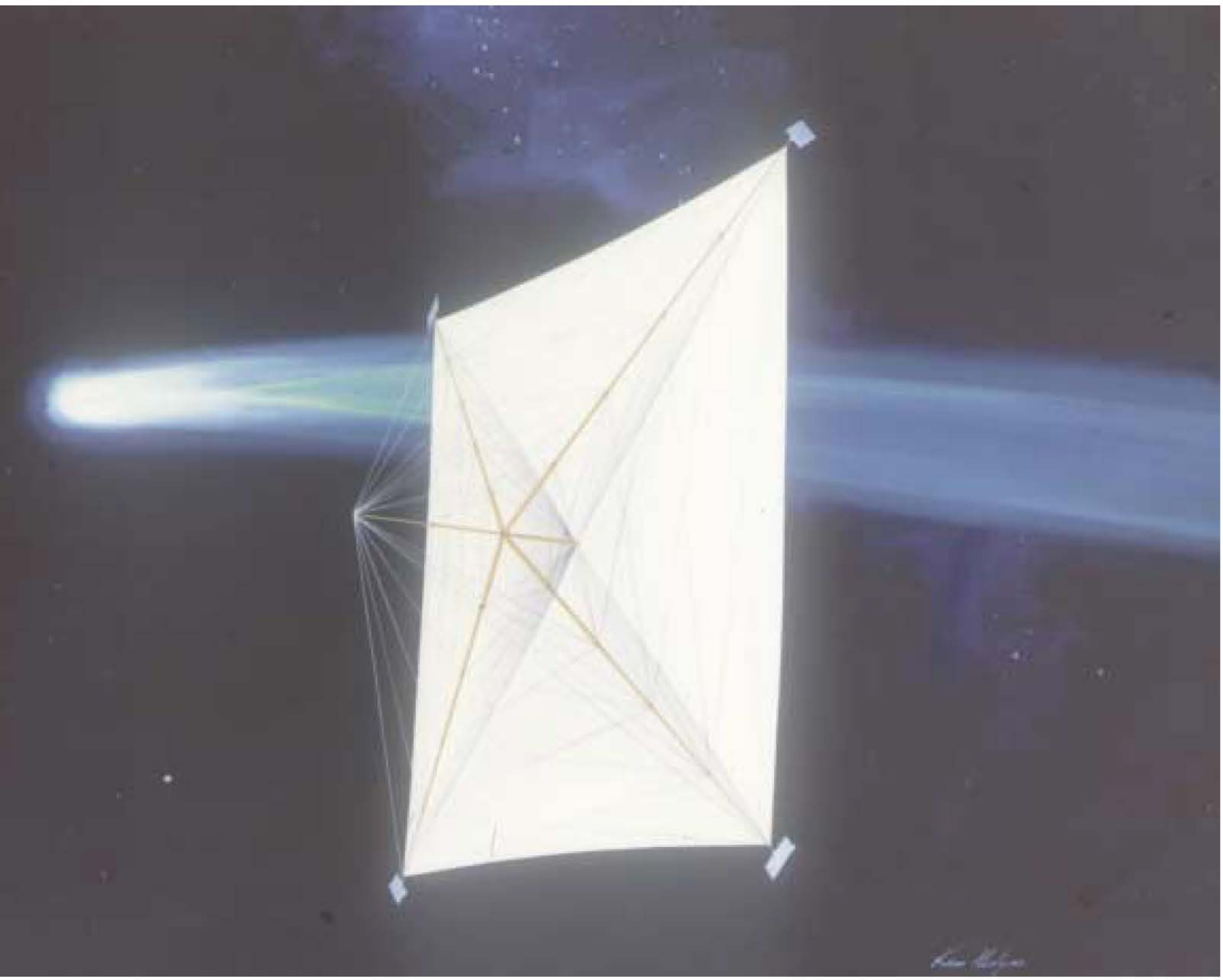
Earthquakes, floods, and landslides: would you want to live in this Chinese village?

But what we *can* plan for, we should. The little Chinese village below is a city that is waiting to die. This city has everything going against it. It sits on an active alluvial fan that could well bury it in a flood. It has an active mountain front; there's a beautiful normal fault right at the base of the mountain. Talus from seismic shaking could bury the city in rocks. There are clear signs of young landslides. So there's flooding, faulting, rock falls, and landslides. This is a place you don't want to spend a lot of time! As world population grows from 6 billion to 12 billion or whatever it's going to be in the next 50 years, we have an opportunity now that will not come around again—an opportunity to choose the places that we're going to expand into. When the Taiwanese and Turks expand into the mountains, I hope they avoid places where landslides can happen. When they expand further onto the coastal plains, I hope they are aware of the potential for slumping and liquefaction. And when they build near their faults, I hope they choose to mitigate against ground ruptures. They need to talk to their local geologists, who can advise them on how to avoid all these natural hazards.

We have a clear choice: we can live with our beautiful, dangerous Earth as we have in past millennia, or we can learn where to put our bridges, campuses, houses, and factories to minimize the destruction. On my best days, I'm optimistic that we will choose a new vision for the future rather than acquiesce to enduring the damage and death brought by natural disasters as we have in the past. □

Professor of Geology Kerry Sieh has been a member of the Caltech faculty since 1977, the same year he earned his PhD from Stanford; his AB (1972) is from UC Riverside. Sieh is a paleoseismologist, that is, he studies the patterns of earthquakes from the perspective of a geologist, over hundreds to thousands of years. His initial interest in the San Andreas fault has expanded to include faults all over the world, motivated by a concern for human welfare. This article is adapted from the Watson Lecture he gave in the spring of 2000. Since then, devastating earthquakes in El Salvador and India have provided additional examples of poor land-use planning.

Kepler observed in 1619 that a comet's tail faces away from the sun, and concluded that the cause was outward pressure due to sunlight—a force that might be harnessed with appropriately designed sails.



Solar Sailing: The Next Space Craze?

by Joel Grossman

A proposed solar-sail mission to fly alongside Halley's comet in 1986 may have been ahead of its time. It was killed by NASA in 1977, partly on the grounds that the technology was unproven. But the idea keeps coming back—sails don't need to carry their own fuel, making them very attractive to mission planners. And now the hardware is starting to catch up with the hype. Rendering by Ken Hodges.

With a name like solar sailing, the technology sounds like it could be Southern California's next beach-sport craze. But the Jet Propulsion Laboratory (JPL), which is managed for NASA by Caltech, is planning to leave the Pacific Ocean far behind. Plans on the drawing board run the gamut from communications satellites hovering over Earth's poles, held in position by solar sails, to spacecraft hoisting giant, ultrathin sails for journeys exploring interstellar space.

Perhaps the grandest mission of all will be an interstellar probe. Its destination: Alpha Centauri, the sun's nearest neighboring star, approximately four and a half light-years away. Lasers as powerful as 10,000 suns, focused on the craft from Earth-orbiting satellites, could one day accelerate such a probe to one-tenth the speed of light. At that clip, it would reach Alpha Centauri within the professional lifetime of a scientist, arriving there in 40 to 50 years.

But that's going to be a while. JPL scientists estimate that a more near-term precursor spacecraft powered only by sunlight could cover the 25 trillion miles, or 273,000 astronomical units (AUs; an AU is 93 million miles, or 150 million kilometers, the average distance between Earth and the sun), at a speed of 15 AUs per year. This is equivalent to flying from Los Angeles to New York City in 63 seconds, about nine times faster than the orbital speed of the Space Shuttle. At 160,000 miles per hour, the solar-sail probe would be speeding through space five times faster than the 3-AU-per-year speed of Voyager 1, a conventionally propelled spacecraft launched in 1977 that is currently our most distant space probe. An interstellar precursor mission launched in 2010, the earliest projected date, would overtake the then-41-year-old Voyager 1 in 2018. It would take 100 millennia for Voyager 1 to reach Alpha Centauri, but only 20 millennia for the sailcraft.

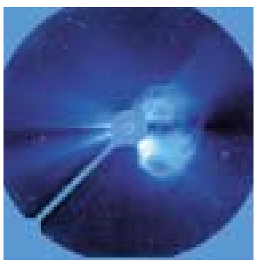
"We are *hoping* for a demonstration mission by 2005, with an interstellar precursor mission launch in the period 2010 to 2015," said Sarah Gavit, associate manager for JPL's Interstellar Program and preproject manager of the Interstellar Probe Mission until January 2001. "There are many other technologies that need development for interstellar or even near-interstellar travel. For example, communications, autonomy, etc. Sails are getting ready for flight demos, while some of these other technologies are still a ways off." Adds Chuck Garner, senior engineer in JPL's gossamer systems group, propulsion and thermal engineering section, "The sailcraft will be at very great distances from Earth, and therefore must operate and navigate itself without the aid of ground controllers. And communications hardware must be developed that can transmit data over enormous distances, utilizing very little power and requiring very little mass." To deal with these parallel technology needs, JPL created a Solar Sail Program to develop the solar sails, and a separate Interstellar Program is developing the other technologies.

Meanwhile, the National Oceanic and Atmospheric Administration (NOAA), the National Weather Service, the Department of Energy, the Air Force, the Department of Defense (DoD), and the Space Environment Center in Boulder, Colorado, are eyeing solar-sail technology for more immediate practical applications. These include monitoring the sun for magnetic storms that can knock out communication and Global Positioning System (GPS) satellites, and play havoc with such earthbound things as electrical power grids and cell phones. This would require an orbit around the sun on a path that keeps the spacecraft directly between the sun and Earth at all times. However, this disobeys Kepler's laws of orbital mechanics, and such a satellite would need to carry a massive amount of propellant to fight the tendency to move out of the desired orbit. But propellantless propulsion via solar sails could keep satellites in such orbits—or in stationary orbits over Earth's poles, which are similarly non-Keplerian. Earlier

Right: Kepler's law says that objects in smaller orbits travel faster, so within, say, a month, a sun-orbiting early-warning spacecraft would be out of line with Earth.

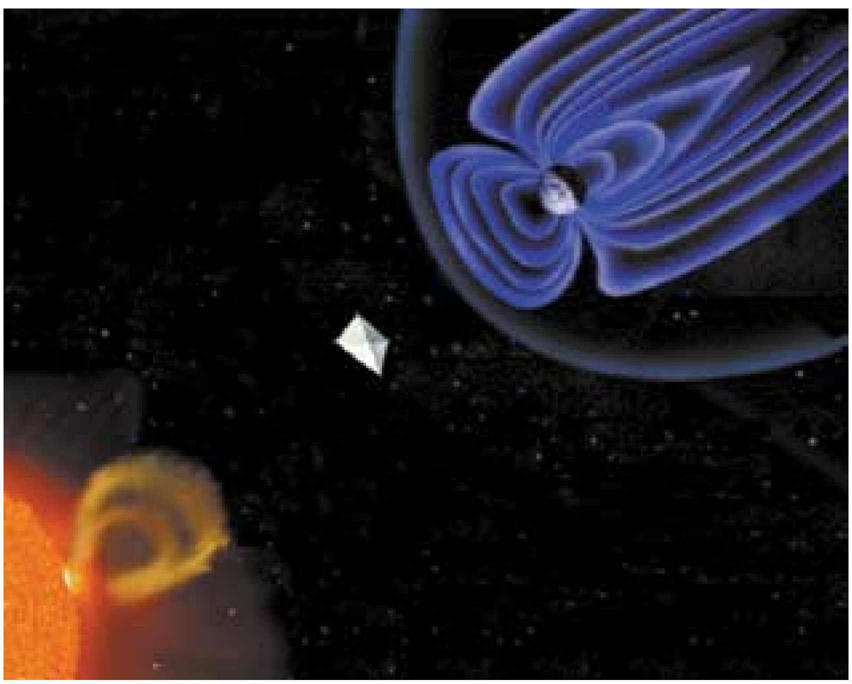
Below: A large coronal mass ejection, or solar storm, on April 20, 1998 as seen by the Large Angle and Spectrometric Coronagraph aboard SOHO. The central disk covers the sun, but the white circle in the disk's middle shows the sun's size (about 1,400,000 kilometers in diameter) and position.

Bottom: Geostorm on station.



warnings of inclement space weather would allow utilities more time to boost power reserves, provide wireless users time to prepare for transmission failures, and in extreme cases allow satellites time to go into "sleep" mode until the storm passed. And satellites permanently hovering over the North Pole would for the first time allow continuous monitoring of areas now only intermittently sampled by orbiting satellites. This round-the-clock surveillance of, for example, polar ice and the aurora borealis, or northern lights, could spur advances in meteorology, climatology, and oceanography. Other applications include search and rescue support, communications, and data relay over the poles.

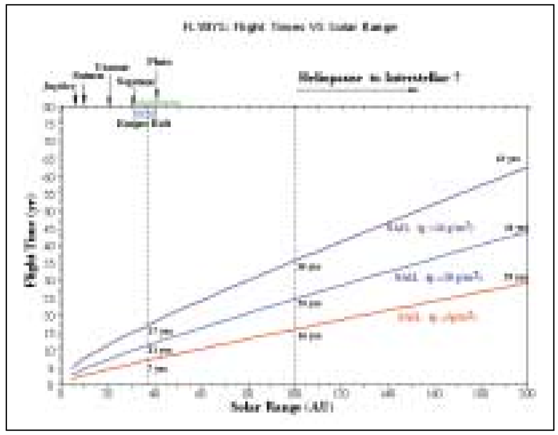
After early input from JPL, both NOAA and the DoD are planning a joint mission known as Geostorm, which will monitor space weather and the solar wind—a steady sun-produced stream of ions, electrons, and neutral atoms that is perhaps best known for interacting with the ionosphere to create the northern lights. The best space-storm warnings currently come from NASA's Advanced Composition Explorer (ACE), which along with the joint NASA/European Space Agency (ESA) SOlar and Heliospheric Observatory (SOHO) is "parked" about 0.99 AU from the sun, at the point where the gravitational forces of the sun and Earth balance each other. (This is called the first sun-Earth Lagrangian point, or L1.) However, Geostorm will be maintained in a similar position 0.98 AU from the sun, doubling the warning time for potentially disruptive storms from one to two hours. The photon pressure on a solar sail 67 meters on a side will counteract the sun's "extra" gravity to keep Geostorm sunward of L1. Another mission known as the Solar Polar Imager would further bolster scientific knowledge of the solar wind and geomagnetic storms via an orbit that passes over the sun's still largely unexplored north and south poles—an orbit that's hard to achieve conventionally because of the enormous amount of propellant required to leave the equatorial plane in which the planets move.



And solar sails could be a boon to planetary exploration. Mercury could be better studied from a sun-synchronous orbit about the planet, for example, which a solar sail would make feasible. Solar sails could also be useful for asteroid rendezvous, and for reducing the travel time needed to explore the outer planets and their many moons—a particular benefit in the case of sample-return missions. And the cost of transporting large amounts of cargo and equipment between Earth and, for instance, Mars to establish a permanent human presence could be so dramatically reduced that it would become practical financially.

Some attribute the idea of hoisting sails in outer space to the aforementioned Johannes Kepler, who

Estimated flight times to the outer solar system and beyond for a 500-kilogram solar-sail payload launched from a Delta II rocket. (For comparison, the 815-kilogram Voyager 2 took 12 years to reach Neptune after launch on a much larger Titan Centaur. Without the gravity assists from Jupiter, Saturn, and Uranus, it would have taken 30 years.) The sail's density per unit area is denoted by "g," and the green bar represents the range traversed by Pluto's wandering orbit. The Kuiper belt is a zone of icy material that managed to elude the outer planets during their formation.



four centuries ago wrote fellow astronomer Galileo a letter mentioning space travel using a "ship or sails adapted to the heavenly breezes." Kepler observed in 1619 that a comet's tail faces away from the sun, and concluded that the cause was outward pressure due to sunlight—a force that might be harnessed with appropriately designed sails. At the time, the corpuscular theory of light was in vogue, which turns out to be qualitatively consistent with today's quantum-mechanical view that light, in some cases, acts as a particle instead of a wave.

Scientific understanding moved closer to the mathematical basis for designing a working solar sail in 1873, when physicist James Clerk Maxwell, who is associated with the wave theory of light, predicted the existence of radiation pressure as a consequence of his unified theory of electromagnetic fields. Radiation pressure was independently shown to exist in 1876 by Adolfo Bartoli, who derived it mathematically from the second law of thermodynamics. Radiometers, invented by Sir William Crookes, were initially, albeit mistakenly, used to demonstrate the existence of radiation pressure in 1873—a classroom demonstration that is still done today.

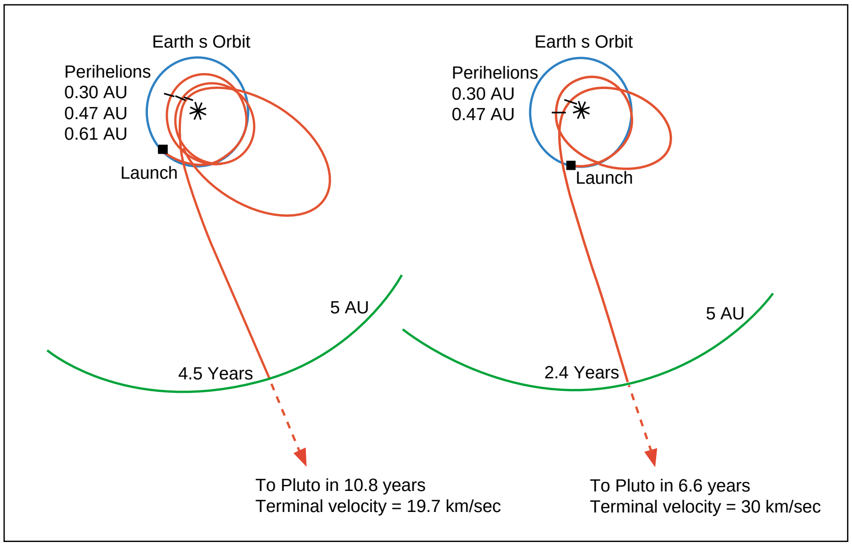
In fact, the force driving a radiometer is due to thermal-molecular forces, and is several orders of magnitude greater than radiation pressure. This type of levitation has recently been demonstrated by Energy Science Laboratories, Inc. (ESLI) of San Diego, under contract to JPL. "These experiments are part of a project to produce a spacecraft that can be launched from your backyard to the stars, using an assortment of different kinds of physics derived from photon interactions," says Henry Harris, chief scientist for space solar power at JPL and task manager of the project. This type of levitation only works where there's an atmosphere—but not too much of one!—so the scheme actually has four components. The fragile sail would be gently lofted on a carbon-fiber balloon to a sufficient height for the thermal-molecular effect to work. Then, when the air peters out, the sail continues to rise as the photon beam heats its underside enough that atoms in a special coating begin to evaporate off it, creating thrust. And upon reaching Earth orbit, it kicks over to purely photonic propulsion. Harris's team has demonstrated each of these four technologies individually, but putting them all together will take an enormous amount of additional work.

A carbon disk made by ESLI levitates in the light from a 100-watt bulb.

What is now accepted as the first true experimental verification of the existence of radiation pressure came from Russian physicist Pyotr Lebedev's elegant torsion balance experiments at the University of Moscow in 1900. Independent verification came from Ernest Nichols and G. F. Hull at Dartmouth College in 1901. But the modern concept of light as photons—massless packets of energy capable of producing momentum transfer, or radiation pressure—did not evolve until the early 20th century as Max Planck, Albert Einstein, and others grappled with thermal radiation and the then-puzzling nature of the photoelectric effect.

Indeed, as Colin McInnes notes in his book, *Solar Sailing: Technology, Dynamics and Mission Applications*, the term "photon" was not even coined until 1925. By this time, Einstein had won the Nobel Prize for explaining the photoelectric effect, and the equation $E = mc^2$ had become part of the modern lexicon (and *Time* magazine cover material!). The amount of momentum transferred from a photon to a solar sail is derived by combining quantum mechanics and Einstein's theory of special relativity. Both McInnes and former JPL employee Jerome Wright in his earlier book, *Space Sailing*, detail the mathematics needed to calculate radiation pressure, plot trajectories and orbits, and begin designing a solar sail, starting with Planck's law and Einstein's mass-energy equivalence.

Perhaps not surprisingly, science-fiction writers



A comparison of two sun-diver trajectories to Pluto. "Perihelion" refers to a point of closest approach to the sun. The three-loop trajectory at left is for a 270-square-meter sail with a density per unit area of 10 grams per square meter, and provides an initial acceleration of 0.5 millimeters per second per second. The faster flight at right assumes a 380-square-meter sail with half the areal density and twice the initial acceleration.

of the late 19th and early 20th centuries were also transfixed by light, and were penning tales of spacecraft propelled by mirrors. That is the principle of the solar sail: a photon reflecting off a shiny surface gives that surface a push equal to twice the photon's momentum. (The surface gets one dose of momentum in slowing the photon down and stopping it, and another one in accelerating it back in the opposite direction as it is reflected.) The catch is that because photons have no mass, and thus very little momentum, the mirror has to be featherlight in order to be moved significantly. The first really practical writings on solar sails are attributed to Konstantin Tsiolkovsky, the self-taught father of astronautics in the Soviet Union, and his Latvian colleague, Fridrickh Tsander, a liquid-propulsion rocket pioneer. In the early 1920s, the pair (their work appears to have been independent) wrote up their notions of very large, ultrathin mirrors propelled to "cosmic velocities" by the pressure of sunlight, a design concept still current.

After Tsiolkovsky and Tsander, solar sailing faded into oblivion for almost three decades, during which liquid-fueled rockets became the rage. The first American solar-sailing proposal, in the May 1951 issue of *Astounding Science Fiction*, appeared under the byline Russell Sanders—a pseudonym adopted by aeronautical engineer Carl Wiley to guard his professional reputation. The Sanders/Wiley article proposed using solar sails instead of rocket propulsion for interplanetary travel, and detailed what is now the usually accepted plan—to start the journey by spiraling in close to the sun to gain maximum momentum where the photon concentration is highest.

During the next decade the matter became a serious scientific subject, and Richard Garwin of Columbia University coined the term "solar sailing" in a 1958 article in the journal *Jet Propulsion*. Several studies in the next few years showed that solar sailing could theoretically equal or exceed the velocities attainable via chemical or ion propulsion for a number of missions. And, for fixed sail angles relative to the sun, solar-sail orbits were calculated to be logarithmic spirals. (If the spacecraft is inbound toward the sun, this is the exact equivalent of a moth's death spiral around a porch light, and for the same reason—the light is kept at a constant angle to the flight path.) But it was famed science-fiction writer Arthur C. Clarke's melodramatic 1963 short story, "The Wind from the Sun," that gave the idea its biggest push, capturing the public imagination and spreading the concept among sci-fi–reading engineers—who quickly figured out that the solar wind lacked the propulsive force of the sun's photon stream.

By the 1970s NASA was funding solar-sailing studies, and JPL's Wright came up with a trajectory for a solar-sail spacecraft to rendezvous with Halley's comet and watch it evolve as it neared the sun. Bruce Murray, who was then JPL's director and a Caltech professor of planetary science, elevated the idea to most-favored "purple pigeon" status. Two competing designs were produced: a three-axis-stabilized, square-shaped sail 800 meters on a side; and a "heliogyro" some 15 kilometers in diameter that sported 12 free-spinning, helicopter-like blades, designed with the help of helicopter engineers John Hedgepeth and Richard MacNeal. However, NASA dropped the project and its large payload in 1977, leaving Halley to conventionally propelled flybys (a much easier mission!) by spacecraft from the Soviet Union, Japan, and Europe. One reason the mission was shelved was that the deployment of a solar sail in outer space was considered a high risk. Indeed, a free-flying solar sail has not been deployed in space to this day.

Nevertheless, solar sailing had by then attracted an almost cultlike following, and several newly formed international organizations began promoting races to the moon and Mars, eerily reminiscent of Clarke's short story. JPL engineer Robert Staehle, who is now deputy manager of the Europa Orbiter Project, helped form the World Space Foundation in 1979 and attempted to obtain private funding for demonstration flights. Europeans formed the Union pour la Promotion de la Propulsion Photonique (U3P) in 1981, and along with the Solar Sail Union of Japan promoted a race to the moon. Solar-sail fever was still going strong in 1989, when the Christopher Columbus Quincentennial Jubilee Commission attempted to organize a race to Mars for 1992. Although they kept alive interest in solar sailing and encouraged designers to advance the art, the prize money and space-sailing contests never materialized.

The days of such promotions are over, at least for now, though other schemes worthy of the best of P. T. Barnum are taking their place. For example, Encounter2001.com, whose Web site also hosts ads for burials in space, is working with L'Garde, Inc., of Tustin, California, which specializes in inflatable space structures, on an interstellar spacecraft. Encounter2001 hopes for a live, members-only Webcast of its privately launched solar sail, which will double as a giant billboard and carry a payload of photos and greetings from customers who are expected to flock on line to pay by credit card as the launch date nears. For $24.95, you get a photo and a message; for another $25, you can send a "biological signature"—a sample of hair-follicle DNA.

Meanwhile, back at the lab, JPL's New Millennium Program (NMP), which solicits proposals to demonstrate new spaceflight technologies and funds the winners, has taken up the torch. NMP's Space Technology 7 (ST7) announcement in April 2001 is expected to include an opportunity for a full-flight solar-sail mission, says Hoppy Price, manager for solar-sail technology development in the NASA Technology Program Office at JPL. Price hopes to place a solar-sail satellite into a high equatorial orbit, deploy the sail, and then just let it fly around. The goals are twofold: first, to simply prove that it can be deployed; and second, to evaluate attitude-control issues, thrust performance, structural dynamics, and sail lifetime, and to prove out the control algorithms in the flight software. This will clear the way for "operational missions" like DoD and NOAA's Geostorm.

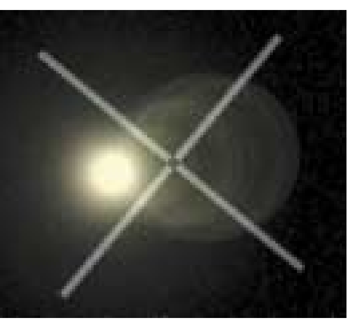
But the title of First Solar Sail in Space may go to the nonprofit Planetary Society, whose Pasadena headquarters is just a mile or so from the Caltech campus. As *E&S* was going to press, the society announced that it had contracted with Russia's Babakin Space Center to build a 600-square-meter, windmill-shaped sail 30 meters in diameter. The sail's deployment mechanism, which uses inflatable booms, will be tested on a subor-

Above: The World Space Foundation displayed a prototype solar sail on the floor of the Pasadena Convention Center at the Planetary Society's first Planetfest in 1981. Right: A panel of the Planetary Society's current solar sail, which is being assembled near Moscow. The Mylar sail is a relatively thick five microns, about one-fifth the thickness of a trash bag; April's suborbital flight test will include two such panels. And in a peace dividend from the end of the Cold War, both the suborbital test and the completed spacecraft will be launched in converted intercontinental ballistic missiles fired from a Russian nuclear sub in the Barents Sea. Far right: The completed spacecraft will carry two cameras and several instruments and, although just a point of light as seen from Earth, will shine as brightly as the full moon.

bital flight in April, as will a pioneering inflatable reentry shield the Russians have developed. The spacecraft itself is slated to be launched to an initial altitude of 850 kilometers between October and December 2001 to attempt the first solar-sail flight. "It's the Wright Brothers analogy," says Louis Friedman, the Planetary Society's cofounder and executive director. "This first sail won't fly to a distant location, but we hope it will demonstrate the concept." (Incidentally, Friedman led the Halley's comet solar-sail project at JPL.) This commercial venture, named Cosmos 1, is being privately funded by Cosmos Studios, a new-media company started by Ann Druyan, wife of the late Carl Sagan, who cofounded the Planetary Society with Friedman and Caltech's Bruce Murray; and Joe Firmage, an Internet entrepreneur.

Deploying a solar sail in space is fraught with structural-engineering complexities. The packaging is particularly tricky, as the stowed sail's exposed area may expand over a hundredfold as it unfurls. Risks inherent in unpacking solar sails in space include the sudden venting of air trapped in the folds of the sail, with enough force to tear it; tangles; rips in the fabric; electrical arcs or other discharges; and electrostatic forces—static cling, in other words—that may hold the folded sail together. "The folded-up sail is essentially a big capacitor," says Price. "We do not know how it will behave in space." Grounding can be designed-in to minimize some of the electrical-discharge risk, but it is "a bit hard to analyze on the ground." Thus, actual launches are needed to see how it works. Wrinkle management in the packing and unfurling is vital, because wrinkles can cause multiple reflections and intense hot spots that might damage the sail, and wrinkles will also decrease the sail's reflective performance. The sail's wrinkle potential will probably vary with the manufacturing process; wrinkle-management options being explored include special sail-fabrication machines that fold the sail wrinkle-free on a big table as it is built, and methods of pulling out the sail with enough tension to remove the wrinkles.

A number of sail shapes are likely to prove viable, including squares, hexagons, and other polygons, as well as disks and hoops. Carnegie Mellon University is reviving the heliogyro, albeit a more modest one with four blades 30 meters long and a meter wide. JPL is starting out with a simple design made up of four triangular panels. "It looks like a big kite with four booms coming out from the center," says Price. The four booms will deploy themselves straight out from the central hub to unfurl the sail.

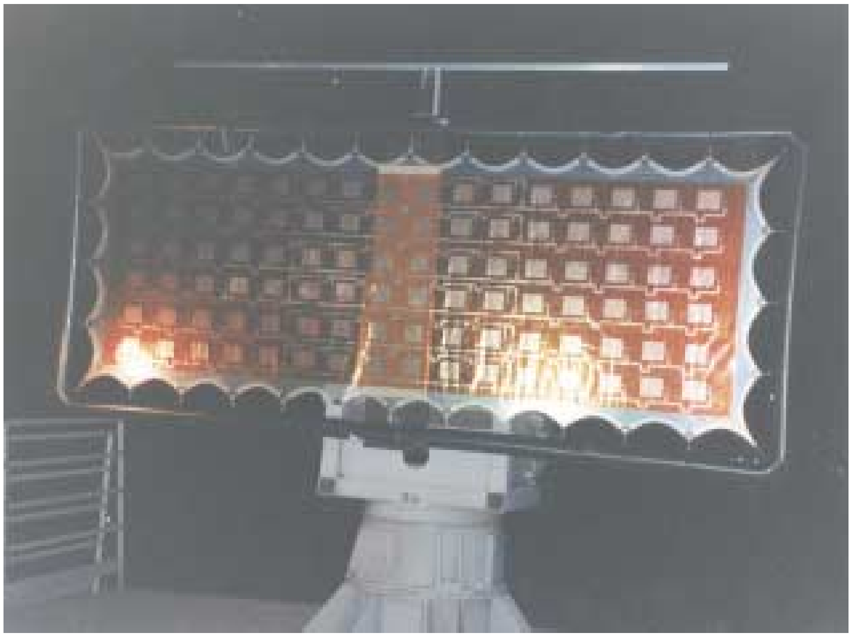


Above: The Carnegie-Mellon heliogyro. Right: The DLR's lens-shaped boom will be used in ESA's solar-sail program, which is planning a test flight in a year or so.

Houfei Fang, a member of the technical staff in JPL's gossamer systems group, holds two five-meter-long, three-inch-diameter STR booms. (One of them is rolled up on a six-and-a-half-inch diameter mandrel, as seen in the inset.) The boom weighs a kilogram, and can take a maximum axial force of 75 kilograms.

Several types of booms are being considered. One option is carbon-fiber booms, developed by the German Aerospace Center (DLR), that are lens-shaped in cross section. They lie flat when rolled up on a spool, but pop open as they unroll, becoming quite stiff. (The prototype sail built by the World Space Foundation in 1981 used similar tubes made of much heavier stainless steel.) Another novel design, recently patented by JPL, uses commercial-grade stainless steel carpenters' measuring tapes (from Sears!) as stiffeners. Called a Spring-Tape Reinforced (STR) aluminum laminate boom, it also rolls up flat, but has a circular cross section when deployed. Also under consideration are carbon or fiberglass rods in the form of a cross-braced, three-sided truss. When twisted, the truss coils up to stow compactly into a cylinder the size of a small trash can.

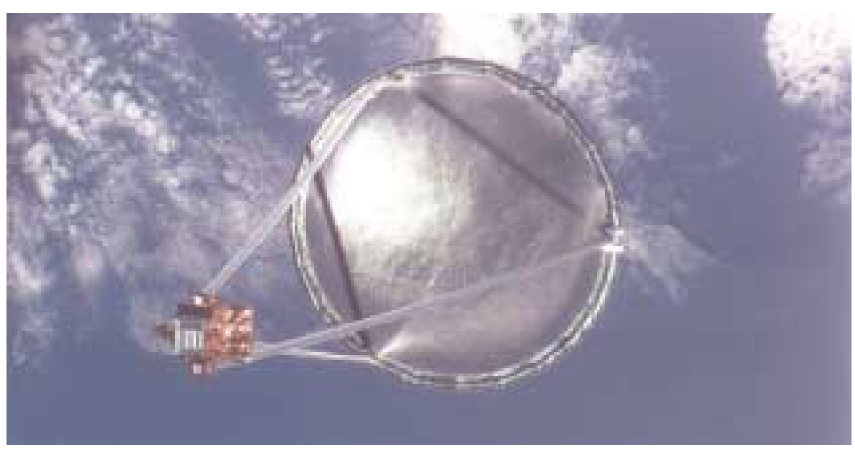
Inflatable booms that blow up like long, skinny balloons have the potential to unfurl a tightly rolled sail from its container, and, if properly stiffened—perhaps by being perfused with an epoxy that cures into a very hard plastic when



The overall size of the inflatable synthetic aperture radar array above is 1.7 by 3.7 meters, yet it rolls up into the two scrolls at right for stowage. The antenna, which is a flat sheet, acts like a traditional parabolic dish antenna thanks to a tiny copper dogleg incorporated into each reflective element that steers and focuses the radar beam—the brainchild of John Huang, a principal engineer in JPL's Spacecraft Telecommunications Equipment Section.

exposed to ultraviolet light—could then function as rigid struts to keep the sail taut. The deployment of an inflatable antenna in orbit has been demonstrated. The Spartan 207/Inflatable Antenna Experiment, which flew in May 1996 on space shuttle *Endeavour*, deployed a 14-meter antenna for several hours. "The demonstration was a success, and we learned a lot from it, but the process of inflation was not well controlled," says Price, which means the technology needs more testing in space.

JPL and its industrial and academic partners are currently developing inflatable structures for a variety of applications, including solar arrays, radar and communications antennas, telescopes, and all kinds of instruments. So solar sails will benefit from research directed toward projects like the construction of lightweight, inflatable space telescopes with minimal steel and glass, such as JPL's proposed Advanced Radio Interferometry between Space and Earth (ARISE) mission. ARISE is designed to look at the disks of gas and dust that surround black holes, zooming in on them with a resolution 5,000 times better than that of the Hubble Space Telescope.



Right: The 14-meter Spartan 207/Inflatable Antenna Experiment in flight.

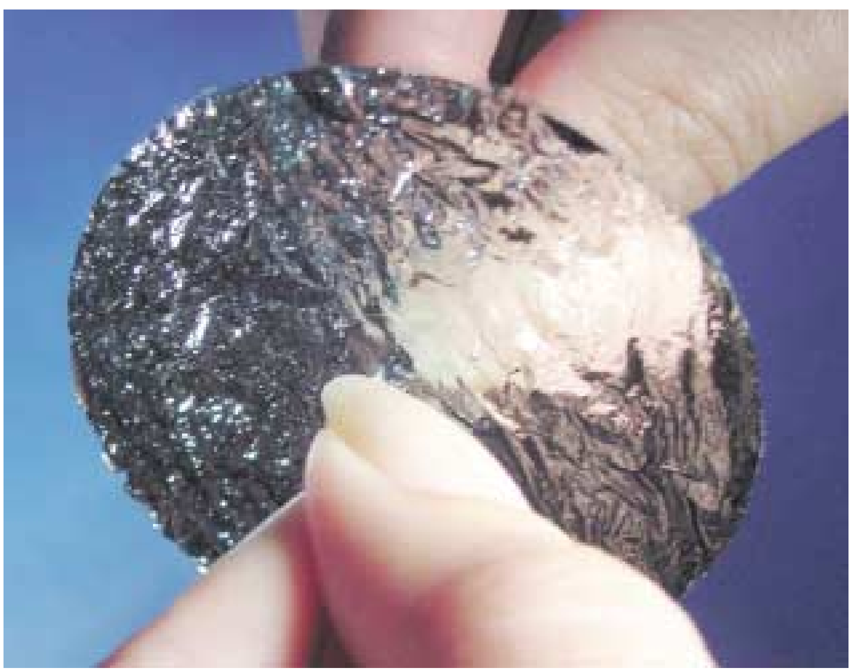
The Russians have twice attempted to deploy large, sail-like mirrors in space. The wheel-like mirrors, named Znamya ("Banner"), were spun on motor-driven axles to keep their shape through centrifugal force. A 20-meter-diameter version was successfully tested by Vladimir Syromiatnikov and colleagues at Energia in 1993, using a *Progress* resupply vehicle that had just undocked from the *Mir* space station. However, a 25-meter version failed in 1999, when it tangled on an antenna jutting out from the *Progress* spacecraft that was deploying it. The antenna had been used in the docking maneuver, and was supposed to have been retracted before sail deployment. A mission-operations software error was to blame.

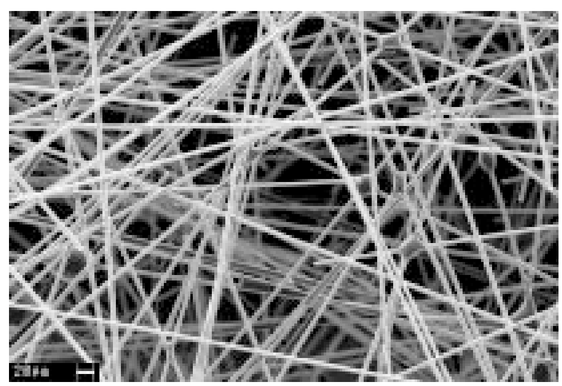
Once a sail is deployed, steering it and controlling its attitude (i.e., pitch, yaw, and roll) become paramount concerns. Thrusters could be used for steering, but the whole idea behind sails is to avoid the weight of propellant and the possibility of running out of it. One approach is to shift the spacecraft's mass relative to the sail's center of pressure by moving the spacecraft's electronics package around on the end of a long boom. Alternatively, the spacecraft could be steered like a sailboat by moving the center of pressure relative to the center of mass by use of adjustable vanes or flaps on the outer corners of the sail. "We expect to see different, competing ideas on how to control attitude," says Price.

Thin plastics like Mylar and Kapton are the major near-term candidates for solar-sail fabrication, as they're lightweight and are commercially available in wide rolls. Mylar can only be used for short-duration missions, as it is rapidly degraded by ultraviolet light. Kapton is chemically inert, has high radiation resistance, adheres well to metal films and adhesives, and does not degrade until 670 kelvins (K)—the melting temperature of glass, and well above the 520–570 K range considered safe for long-term solar-sail operation.

However, even moderate solar-sail performance requires films on the order of 2 microns (millionths of a meter) thick, which tear very easily and are not routinely fabricated in rolls. Kapton film is typically produced in rolls 7.6 microns thick. Though small-scale etching tests have gotten the thickness down to 0.4 microns, lifting and handling such ultrathin material without tearing—much less folding, packing, and deploying it in space!—is going to be quite a challenge. Suitable Mylar films are easier to come by commercially, and can be had as thin as 0.9 microns. Possible ways to strengthen these films include special backings, such as crisscrossed Kevlar fibers.

Mylar or Kapton needs to be coated with a material like aluminum, which has a reflectivity of close to 0.9 (1.0 being perfect), in order to make it an efficient photon reflector. Even so, some photons will be absorbed and the sail will heat up, especially on missions that go close to the sun. Coating the sail's back side with a substance like chromium, which has an emissivity of order 0.64, is one way to shed heat from absorbed photons and extend the sail's life. (Both metals would be added to the sail by vapor deposition under high vacuum, a common industrial process.) And advanced thermal-control technologies such as micromachined, whisker-like quarter-wave radiators, which act as antennas at infrared wavelengths, would be useful for close approaches to the sun. A typical recent design has 0.1 microns of aluminum vapor deposited on 2 microns of Kapton substrate and 0.0125 microns of chromium





Above: In this microphotograph of ESLI's carbon-fiber mesh, the scale bar is 20 microns long. The fibers are seven microns in diameter, or about one-tenth that of a human hair. The bulk material comes in sheets one millimeter thick, and typically has a density of about seven grams per square meter.

Right: A five-centimeter molybdenum-coated sail sample.

on the rear side, along with grounding straps to guard against electrical discharges between the front and rear surfaces that could cause the sail to tear, and rip stops to limit tearing should it start.

Since the substrate is mainly needed to allow handling, packing, and deployment of the sail, another strategy involves vaporizing the substrate after deployment. This would leave a sail composed of a thin reflective metal film, with rip stops and thick strips of unvaporized substrate left in strategic places to act as reinforcement. Small-scale experiments dating back decades show that it is possible to create metal films 0.05 microns thick, though at some point the film becomes too thin and starts letting a significant amount of light through. One scheme to make metal films lighter without degrading their optical properties involves perforating the films with holes smaller than the wavelength(s) of the light being used for propulsion. Technology to make these small holes already exists in the semiconductor industry.

Since space is a hard vacuum, one could even fabricate the sail in orbit, using a small vapor-deposition unit that would be discarded when the job was done. Direct heating would evaporate, say, powdered aluminum, and the metal would condense onto a sail-shaped substrate. After cooling, the metal film could be separated from the substrate. The technology for manufacturing thin metal films already exists, as do methods for controlling their thickness.

Two years ago there was movement toward graphite fibers for sails, and even more recently toward stronger and possibly thinner single-crystal carbon fibers. Timothy Knowles, president of ESLI (the company that did the thermal-molecular demonstration mentioned earlier), invented a mesh of randomly oriented, crisscrossing graphite fibers called a microtruss. The material, which rather resembles a scrubbing pad, is ultralight, yet stiff and strong. When rolled up or folded into accordion pleats, it springs back into a flat sheet upon release, greatly simplifying deployment. This carbon mesh also takes the heat much better than plastics do, which is vital for laser propulsion. If you want to get to Alpha Centauri within your own lifetime, you need to slam so many photons into the sail that even a near-perfect reflector will start to disintegrate from the accumulated heat it can't reradiate.

In December 1999, JPL funded Leik Myrabo, a mechanical engineering professor at Rensselaer Polytechnic Institute in Troy, New York, to mount a disk-shaped sample of ESLI's microtruss on a sensitive pendulum apparatus, stick it in a high-vacuum chamber, and zap it with photons from a high-powered laser at the Wright-Patterson Air Force Base in Dayton, Ohio. The mesh was coated with a thin layer of molybdenum on one side to maximize its reflectance in the infrared, where the laser operates. The hope was that photonic thrust would deflect the pendulum from the vertical by a measurable amount. The thrust supplied by the laser could then be calculated very accurately by careful measurement of the angle of deflection. However, it was anticipated that the up-to-10-second laser blast would heat the sail enough to cause atoms to evaporate from its surface, giving the pendulum a "kick" as they left. This kind of thrust—the third step in Henry Harris's "backyard launch" scheme—could easily be mistaken for photonic thrust. So the samples were weighed before and after each run, and any thrust due to mass loss was calculated. The research, presented last July at NASA's 36th annual Joint Propulsion Conference in Huntsville, Alabama, showed that the pendulum deflected "from 2.4 to 11.4 degrees, measured as a function of incident laser powers from 7.9 to 13.9 kW. Laser photon thrust ranged from 3.0 to 13.8 dynes," according to the project report published by the American Institute of Aeronautics and Astronautics. The researchers also found that heating the sail to about 2600 K caused ablation, or mass loss, to occur, and those runs produced up to 50 percent more thrust than the theoretical maximum available from photon power alone. "It was amazing what those sails took," says Myrabo. "They were just incredible."

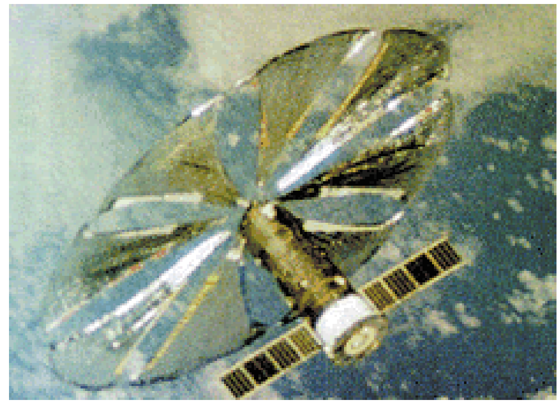
In December 2000 another round of tests was done, in which the sail was propelled up a vertical molybdenum wire. This is considerably more demanding. The pendulum tests translated into a spacecraft acceleration of 0.16 *g*, with one *g* being the force Earth's gravity exerts on you as you sit in your armchair reading this. In order to levitate the sail, it needs to be hit with an upward force in excess of one *g*. The same size microtruss samples were used again, but they were heavier this time because an eyelet to ride the guide wire had to be inserted into them and glued into place. So the sail really had to be zapped hard in order to lift it—in fact, some of the specimens wound up fusing to the wire. Nevertheless, says Harris, "we believe we have demonstrated 1-*g* photonic acceleration at 2600 K. Motion analysis [of the

The world's first demonstration of photonic thrust with a real-world laser-sail material. Laser light first illuminates, then moves a five-centimeter specimen of ESLI's molybdenum-coated microtruss mounted on a magnetically suspended pendulum. The 150-kilowatt continuous CO_2 laser is part of the Laser-Hardened Materials Evaluation Laboratory II, run by the Anteon Corporation under contract to the Air Force at the Wright-Patterson Air Force Base.

videotapes and high-speed movie footage taken of the runs] is currently under way to confirm this. We have also demonstrated small-scale deployment and are beginning stability and control analysis. Theoretical analysis suggests that with further development we may be able to achieve 100 *g* acceleration, which would enable achieving one-tenth the speed of light in approximately eight hours." (Such acceleration would require a sail with one-tenth the areal density and a laser with ten times more power—not unreasonable goals.)

"We have basically demonstrated that it is doable," says Neville Marzwell (MS '71, PhD '73), technology manager for the Technology and Applications Programs Directorate at JPL, though "there are many technological gaps." Sail fabric is getting stronger, and better able to withstand high pressures and temperatures, and Marzwell expects to eventually get to the point where the sail is reinforced with carbon fibers in the form of microdiamonds. Marzwell envisions laser or microwave beams blasting diamond-studded sails to Alpha Centauri with little need for photons from the sun. However, the same sturdy sailcloth would also be useful for "sun diver" missions, like those envisioned by Carl Wiley in his 1951 *Astounding Science Fiction* article, where sails tack in close to the sun to gain maximum momentum.

A parallel program studying microwaves instead of lasers is going on in-house at JPL, using a high-vacuum chamber in the Advanced Propulsion Laboratory, which had previously tested the ion drive for Deep Space 1. The lab also contains a high-power microwave test facility that was adapted for the purpose. Microwaves have several potential advantages as a propulsion beam. Microwave transmitters have been around a lot longer than lasers, and very large, high-power arrays are currently much cheaper to build. (The latter is an important consideration, as a microwave array needs to be considerably larger to support a sail of the same diameter, in order to compensate for the longer wavelength of the microwaves.) And if the sail is designed to absorb some of the microwaves, its interaction with a circularly polarized beam will set it spinning. The torque increases with the beam's wavelength, so the spinning effect works much better with microwaves than it does with lasers. The easiest way to keep a spacecraft on a steady course is to set it spinning perpendicularly to the direction of flight, like a rifle bullet or a well-thrown football. Controlling the sail's spin rate and angle by manipulating the beam's axis of



The Znamya 20-meter mirror used spin to deploy itself and maintain its shape.

polarization would clearly be superior to the heavy laser gyros and thrusters used on today's spacecraft. And the spin could be used to deploy the sail, or to keep it rigid without the use of structural stiffeners, as the Russians did with Znamya. The microwave program is using uncoated samples of ESLI's microtruss, which absorbs about 10 percent of the incoming microwave radiation. The sails were levitated on a guide wire, and in April 2000 the first flights were made. It is still unclear, however, how much of the thrust was photonic, and pendulum experiments are now under way to attempt to resolve this. The spin experiments were less ambiguous—the sail spun at exactly the rate predicted for 10 percent absorption, and when the beam's polarization was reversed, the sail spun in the other direction.

Either way, Marzwell envisions embedding the scrubbing pad with nanocomputers 10 microns square (about one-tenth the thickness of a hair), and instruments to match. A micropump could send captured interstellar material to a nanospectrometer for analysis, for example, while tiny cameras and dust-mote-sized vibration detectors helped navigate the spacecraft and monitor its health. Parallel programs are looking at the technologies, like nanobatteries, needed to make these tiny devices work. "You can't develop a sail without developing the instruments," says Marzwell. In essence, the spacecraft becomes the sail—there's no need for a separate hull dangling below it to carry the payload. This is a major departure from today's paradigm, where 80 to 90 percent of the weight on most missions is fuel and the instrument package seems almost an afterthought. Similarly, a metallic mesh could be embedded into Mylar, which would be evaporated in orbit to leave the

The spacecraft becomes the sail—there's no need for a separate hull dangling below it to carry the payload. This is a major departure from today's paradigm, where 80 to 90 percent of the weight on most missions is fuel and the instrument package seems almost an afterthought.

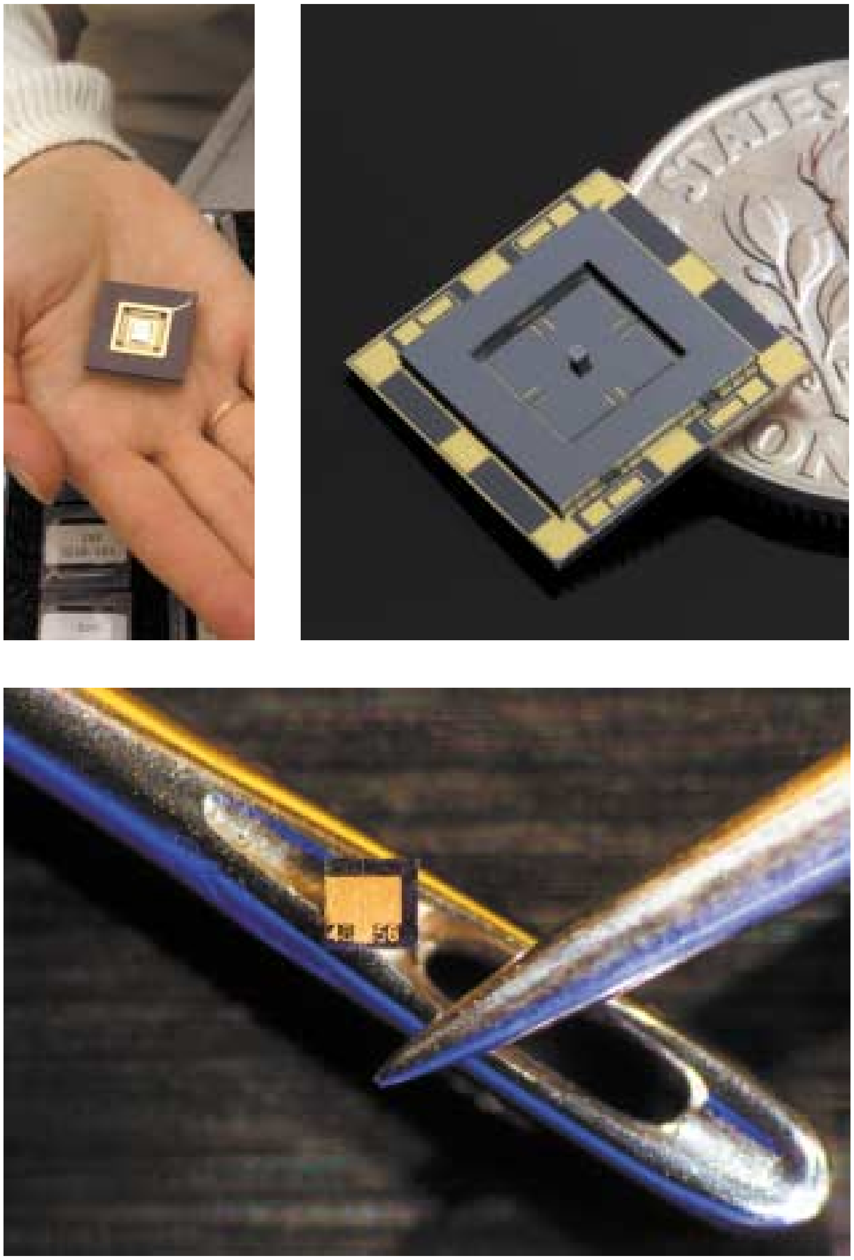
PICTURE CREDITS:
20 – Doug Cummings;
21, 22, 24, 25, 29 — NASA; 20 — SOHO, NOAA; 21, 26 – ESLI;
23 — Richard Dowling/ WSF, Louis Friedman, Planetary Society;
24 — Carnegie Mellon;
24 —DLR; 27 — RPI;
28 — Energia, Ltd.

mesh and its instruments.

Choosing the sail's geometry is a complex problem, involving such variables as how the energy couples with the sail material, and the mechanical and elastic properties of the sail. "Shape is crucial because of the need to control the center of mass and center of gravity," says Marzwell, who believes that a conical, sombrero-like geometry will eventually replace flat sails to obtain maximum photon capture. Such a sail would ride the beam more stably—if the sail's pointy center started to slip off the center of the beam, the asymmetric pressure on the side of the cone would tend to move the sail back into alignment.

Building the laser or microwave facility needed for these missions will be no small feat. Harris's group estimates that the 40-year trip to Alpha Centauri would require a phased laser array 1,000 kilometers in diameter. (Planetary missions can get by with something more modest—a 15-meter array could send a 50-meter-diameter sail carrying a 10-kilogram payload to Mars in 10 days, he says in an article in *Scientific American*.) People are working on those issues, too, but that's another story. . . .

While JPL, the ESA, and the Planetary Society prepare for their first deployment tests with Kapton and Mylar, the advanced concepts and technology people prepare for a more distant, diamond future as they analyze the electrodynamic coupling between high-energy beams and sails varying in shape from thin sheets to balloons. Hopefully, this research will lead beyond missions delivering better space weather reports to explorations of interstellar space that will tell us how the stars, the rocky planets, and perhaps life itself evolved in the universe. □



These solid-state instruments, which could potentially be embedded into an interstellar sail, have been developed by JPL's Center for Space Microelectronics Technology. Top, left: Of course, you've got to have cameras, as well as star sensors for navigation. This is a complementary metal-oxide semiconductor active pixel sensor. It requires one-hundredth the power of a CCD camera, is lighter, and is less susceptible to radiation damage in space. Top, right: A microgyro jointly developed by JPL and Hughes for spacecraft attitude control. Bottom: A tunable diode laser, which can be set like a radio transmitter to emit any given frequency within its range, allowing it to look for molecules of a specific gas.

Joel Grossman is a freelance writer based in Santa Monica, California. He last wrote about solar sailing for the Los Angeles Times Magazine *on August 20, 2000. He also wrote a piece about Professor of Electrical Engineering Yu-Chong Tai's bat-sized flying robot, which appeared in the* Los Angeles Times Magazine *on December 10, 2000.*

For Further Reading

Colin McInnes, *Solar Sailing: Technology, Dynamics and Mission Applications* (Springer-Verlag, 1999)

Jerome Wright, *Space Sailing* (Gordon and Breach Science Publishers, 1992)

Louis Friedman, *Starsailing: Solar Sails and Interstellar Travel* (John Wiley and Sons, 1988)

Scientific American, February 1999

He also has been accused of male chauvinism, anti-Semitism, mistreating his graduate students, and, worst of all, scientific fraud.

In Defense of Robert Andrews Millikan

by David Goodstein

Isaac Newton (framed) and Robert Millikan: colleagues in crime? Speaking of crime, the Newton portrait was stolen from Goodstein's office in 1979. (Photo courtesy of Don Downie, *Pasadena Star-News*.)

Robert Andrews Millikan was the founder, first leader, first Nobel Prize winner and all-around patron saint of the California Institute of Technology, an institution that has given me employment for more years than I care to remember. He also has been accused of male chauvinism, anti-Semitism, mistreating his graduate students, and, worst of all, scientific fraud. Since we at Caltech feel a solemn duty to defend our hero, my purpose here is to tell his story, look into these various accusations, and, to the extent that I can, mount a defense for Professor Millikan.

Millikan was born in 1868, son of a Midwestern minister. He attended Oberlin College, got his PhD in physics from Columbia University, did some postdoctoral work in Germany, and, in the last decade of the 19th century, took a position at the brand-new University of Chicago in a physics department headed by his idol, A. A. Michelson.

During the next decade, Millikan wrote some very successful textbooks, but he made little progress as a research scientist. This was a period of crucial change in the history of physics. J. J. Thomson discovered the electron, Max Planck kicked off the quantum revolution, Albert Einstein produced his theories of relativity and the photoelectric effect, and Jean Perrin's experiments and Einstein's theory on Brownian motion established forever that matter was made of atoms. Millikan made no contribution to these events. Nearing 40 years of age, he became very anxious indeed to make his mark in the world of physics. He chose to try to measure the charge of the electron.

Cathode-ray tubes had been around for decades when, in 1896, Thomson in England succeeded in showing that all cathode rays are electrically charged and have the same ratio of electric charge to mass. This was the discovery of the electron. It was the first demonstration that atoms had internal parts. The challenge then was to measure separately the electric charge of the electron. Thomson and his colleagues tried to do it by observing how an applied electric field changed the rate of gravitational fall of clouds of water droplets that had nucleated on ions in a cloud chamber. The upper edge of the cloud, which had the smallest droplets, could be assumed to contain single charges. In this way, a crude but correct estimate of the unit of electric charge could be obtained. These cloud-chamber experiments were the starting point of Millikan's efforts.

Working with a graduate student named Louis Begeman, Millikan had the idea of applying a much stronger electric field than had previously been used, in the hope of stopping the descent of the cloud completely. To Millikan's surprise, what happened instead was that nearly all of the droplets with their different positive and negative charges dispersed, leaving in view just a few individual droplets that had just the right charge to permit the electric force to come close to balancing the effect of gravity. Millikan quickly realized that measuring the charge on individual ionized droplets was a method far superior to finding the average charge on droplets in a cloud.

It may have been during this period that Millikan's wife, Greta, attending a social event while Millikan spent one of his many long evenings in the lab, was asked where Robert was, according to unpublished remarks by Earnest C. Watson (in the Caltech Archives' Watson papers). "Oh," she answered, "He's probably gone to watch an ion." "Well," one of the faculty wives was later overheard to say, "I know we don't pay our assistant professors very much, but I didn't think they had to wash and iron!"

Unfortunately the single-droplet method had a serious flaw. The water evaporated too rapidly to allow accurate measurements. Millikan, Begeman and a new graduate student named Harvey Fletcher discussed the situation and decided to try to do the experiment with some substance that evaporated more slowly than water. Millikan

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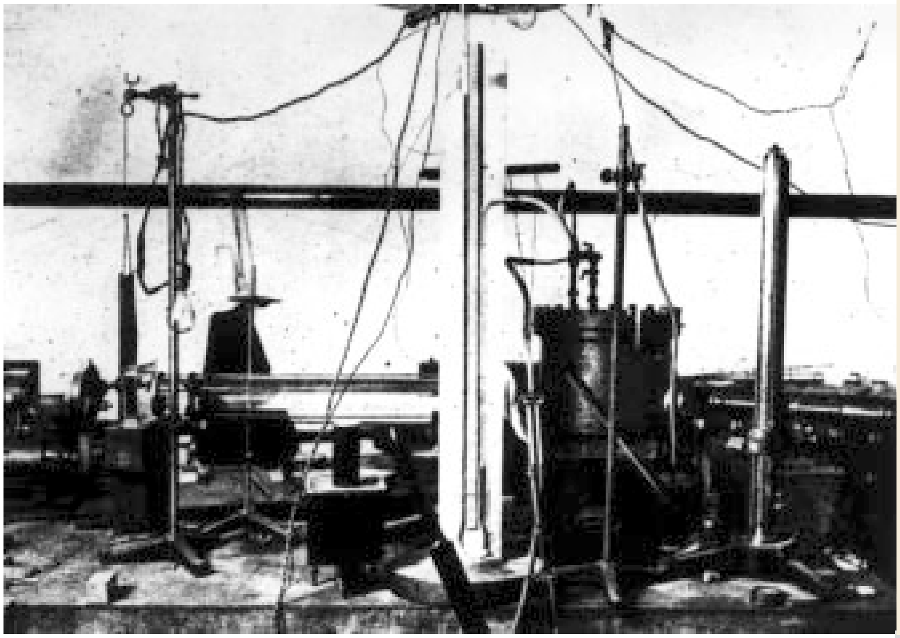
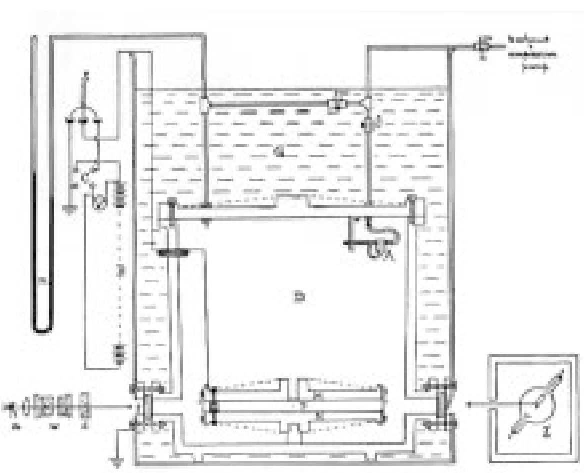
32, 34-35, 37 — Caltech Archives; 36 — American Scientist; 39 — Bob Paz



Millikan's oil-drop apparatus, shown above in his Chicago laboratory, had many components, including the hefty brass chamber (at right, set up for a much later demonstration in 1969). A diagram taken from his controversial 1913 paper (bottom right) shows that the chamber contained two metal plates (M and N) to which he applied a high voltage, generated by a bank of batteries (B). Fine droplets of oil produced by a perfume atomizer (A) were fed into the top of the chamber. A tiny hole in the upper plate allowed the occasional droplet (p) to fall through, at which point it was illuminated by an arc lamp (a) and could be seen in magnification through a telescope. A manometer (m) indicated internal pressure. To eliminate differences in temperature (and associated convection currents), Millikan immersed the brass chamber in a container of motor oil (G), and he screened out the infrared components of the illumination using an 80-cm-long glass vessel filled with water (w) and another glass cell filled with a cupric chloride solution (d). An x-ray tube (X) allowed him to ionize the air around the droplet. With this equipment, Millikan could watch an oil drop that carried a small amount of charge rise when the applied electric field forced it upward and fall when only gravity tugged on it. By repeatedly timing the rate of rise and fall, he could determine precisely the electric charge on the drop.



Millikan proposed that Fletcher be sole author on the Brownian motion work and that he, Millikan, be sole author on the unit-electric-charge work. This is the source of the assertion that Millikan mistreated his graduate students. No doubt Millikan understood that the measurement of *e* would establish his reputation, and he wanted the credit for himself.

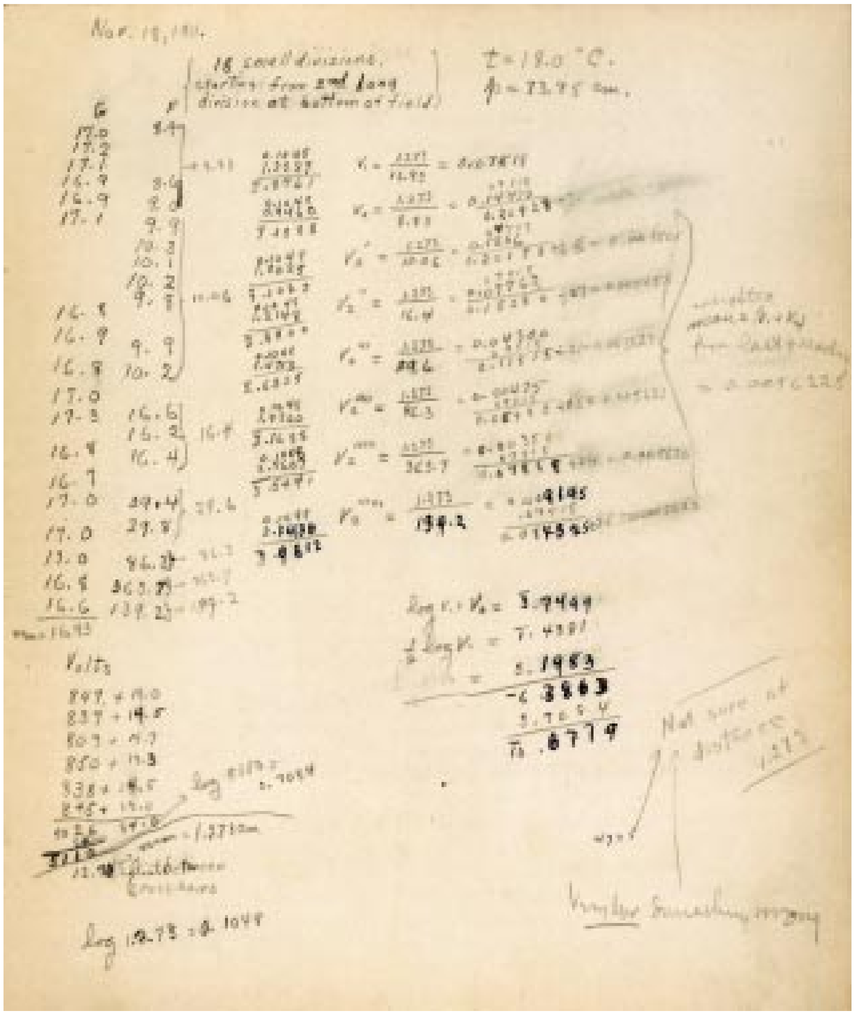
assigned to Fletcher the job of devising a way to do the experiment using mercury or glycerin or oil.

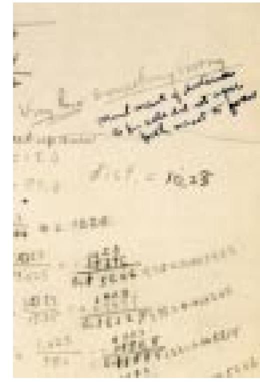
Fletcher immediately got a crude apparatus working, using tiny droplets of watch oil made with a perfume atomizer he had bought in a drugstore. He could view the droplets inside the experimental chamber by illuminating them with a bright light and focusing a specially designed telescope on them. Through the eyepiece, he could see the oil droplets dancing around in what is called Brownian motion, caused by impacts of unseen air molecules. This itself was a phenomenon of considerable current scientific interest. When Fletcher got the busy Millikan to look through his telescope at the dancing suspended droplets of oil, Millikan immediately dropped all work on water, and turned his attention to refining the oil-drop method.

A couple of years later (around 1910) Fletcher and Millikan had produced two results. One was an accurate determination of the unit electric charge (called *e*) from observing the rate of fall or rise of oil drops in gravitational and electric fields, and the other was a determination of the product *Ne*, where *N* is a separate constant called Avagadro's number. The product *Ne* came out of observations of Brownian motion. Millikan approached his student Fletcher with a deal. The academic rules of the time allowed Fletcher to use a published paper as his PhD thesis, but only if he was sole author. Millikan proposed that Fletcher be sole author on the Brownian-motion work and that he, Millikan, be sole author on the unit-electric-charge work. This is the source of the assertion that Millikan mistreated his graduate students. No doubt Millikan understood that the measurement of *e* would establish his reputation, and he wanted the credit for himself. Fletcher understood this too, and he was somewhat disappointed, but Millikan had been his protector and champion throughout his graduate career, and so he had little choice but to accept the deal. The two men remained good friends throughout their lives, and Fletcher saw to it that this version of the story was not published until after Millikan's death and his own.

Let us turn now to the question of scientific fraud. In 1984, Sigma Xi published a booklet called *Honor in Science*. More than a quarter of a million copies were distributed before it was replaced recently by a newer version. *Honor in Science* includes a brief discussion of the Millikan case that begins, "One of the best-known cases of cooking is that of physicist Robert A. Millikan." Cooking, meaning "retaining only those results that fit the theory and discarding others," is one of the classic forms of scientific misconduct, first described in an 1830 book by Charles Babbage (*Reflections on the Decline of Science in England: and its Causes*). According to *Honor in Science,* it is a well-established fact that Millikan cooked his data. What is going on here? There are really two stories. One concerns the question of what actually happened back in the period 1910–1917, and the other illustrates how, much more recently, he came to be accused, tried, and convicted of scientific fraud. It's time to tell both of these stories.

The accusation against Millikan, very briefly, is this. After the 1910 paper (with Millikan alone, not Fletcher, as author) presenting his measurement of the unit of electric charge, Millikan found himself embroiled in controversy with the Viennese physicist Felix Ehrenhaft. Ehrenhaft, using a similar apparatus, found cases of electric charges much smaller than Millikan's value of *e* (Millikan refers to these as "subelectrons"). In order to refute Ehrenhaft's assertion of the existence of subelectrons, Millikan (now working alone; Fletcher had received his doctorate and left) made a new series of measurements, published in 1913, in which the charge on every single droplet studied was, within a very narrow range of error, an integer multiple of a single value of *e*. The 1913 paper succeeded in dispatching Ehrenhaft, and





Millikan's lab notebooks provide some insight into his methods. The page above, dated November 18, 1911, shows his observations at left under G, for gravity, and F, for field, and his calculations to the right. This drop and the ones for which comments are excerpted at top right, were not among those included in Millikan's published paper. The experiment dated March 14, 1912 (opposite page), with its exuberant red notation, was indeed published.

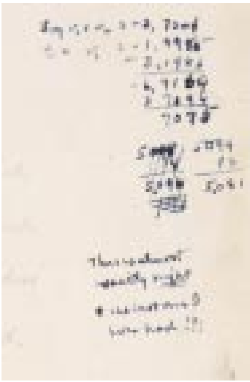
contributed significantly to Millikan's 1923 Nobel Prize. An examination, however, of Millikan's private laboratory notebooks (housed in the Caltech Archives) reveals that he did not in fact report every droplet on which he recorded data. He reports the results of measurements on 58 drops, whereas the notebooks reveal data on approximately 175 drops in the period between November 11, 1911, and April 16, 1912. In a classic case of cooking, the accusation goes, he reported results that supported his own hypothesis of a smallest unit of charge, and discarded those contrary results that would have supported Ehrenhaft's position. And, to make matters very much worse, he lied about it. The 1913 paper presenting Millikan's results contains this explicit assertion: "*It is to be remarked, too, that this is not a selected group of drops, but represents all the drops experimented upon during 60 consecutive days,* during which time the apparatus was taken down several times and set up anew." (Emphasis in the original.) Thus, Millikan is accused of cheating and then compounding his cheating by lying about it in one of the most important scientific papers of the 20th century. There couldn't be a clearer case of scientific misconduct.

Let us look at some of the pages in Millikan's private laboratory notebooks. The one at left is dated November 18, 1911. At the top right the temperature is noted as t=18.0ºC (obviously, Millikan's lab was not well heated for the bitter Chicago weather) and the pressure, 73.45 cm (possibly a stormy day). On the left, we see a column of figures under *G*, for gravity. These were the times taken for a tiny droplet—a pinpoint of light, too small to focus in his telescope—to fall between scratch marks in the telescope's focal plane. These measurements gave the terminal velocity of the drop when the force of gravity was balanced by the viscosity of air. From this measurement alone, he could determine the size of the tiny, spherical drop.

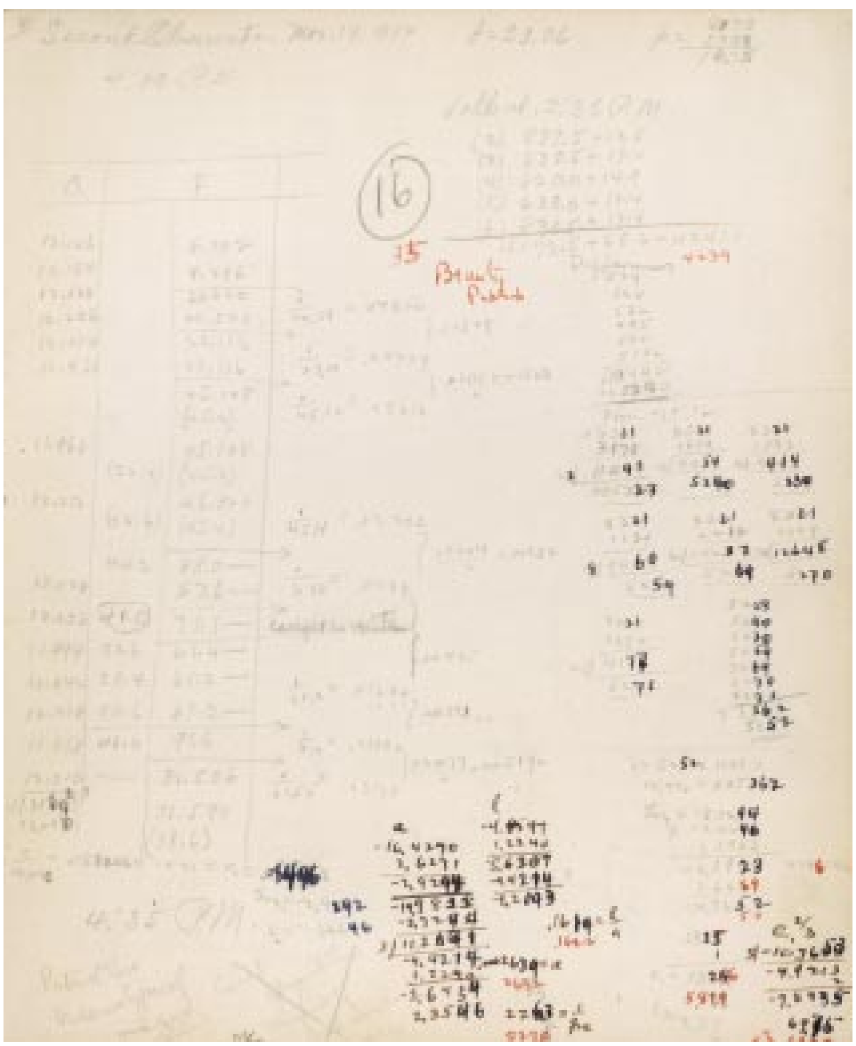
Then there is another column under *F* for field. These were the times taken for the drop to rise between the scratch marks under the combined influence of gravity, viscosity, and the applied electric field, which had been turned off during the *G* measurements. The combined *F* and *G* measurements made it possible to determine the charge on the drop. We can see that the *F* measurements change from time to time. The first series give an average of 8.83, then 10.06, then 16.4, and so on. That happens because the charge on the drop changes from time to time, when the drop captures an ion from the air. Millikan made use of the changes to help deduce the number of units of charge on the drop.

To the right of these columns appears a series of laborious hand calculations (not necessarily done on the same day that the data were taken), using logarithms to do multiplication and square roots, and then finally, bottom right, the comment, "very low something wrong" with arrows to "not sure of distance." Needless to say, this was not one of the 58 drops Millikan published.

Another page shows observations on two drops, taken November 20 and 22, 1911, with similar columns of figures (excerpt above). To the right at the bottom of the first observation we see again "very low something wrong" and below that, "found meas[uremen]t of distance to the hole did not. . . ." Once again, not up to snuff. But on a page dated December 20, 1911 (the temperature now a comfortable 22.2ºC—did the university turn the heat on in December?), we find the remark: "This is almost exactly right & the best one I ever had!!!" (left).



Millikan, in his crucial 1913 paper, did not publish any of the drops for which the raw data are shown in these three pages, not even "the best one I ever had." This was all part of a warm-up period during which Millikan gradually refined his apparatus and technique in order to make the best measurements anyone had ever made of the unit of electric charge. The first observation that passed muster and made it into print was taken on February 13, 1912, and all of the published data were taken between then and April 16, 1912, actually a period of 63 days (1912 was a leap year). Raw data taken during this period are shown in the notebook page below, dated March 14, 1912. Our eye is immediately drawn to the comment, on the top center part of the page, "Beauty Publish."

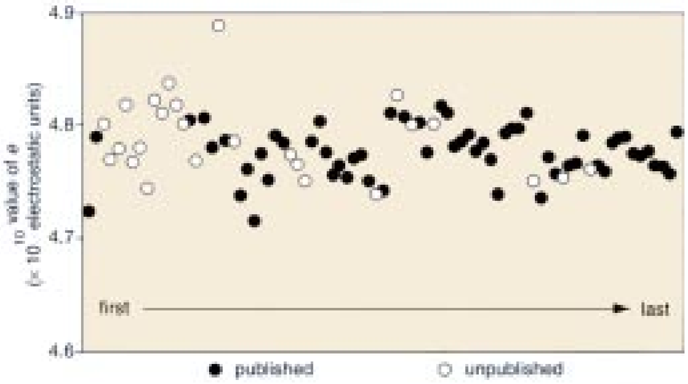


Note also the pressure, 16.75 cm—too low for even the stormiest day in Chicago.

During these 63 days, Millikan recorded in his notebooks data for about 100 separate drops. Of these, about 25 are obviously aborted during the run, and so cannot be counted as complete data sets. Of the remaining 75 or so, he chose 58 for publication. Millikan's standards for acceptability were exacting. If a drop was too small, it was excessively affected by Brownian motion, or at least by inaccuracy in Stokes's law for the viscous force of air (more about this later). If it was too large, it would fall too rapidly for accurate measurement. He also preferred to have a drop change its charge a number of times in the course of an observation, so that he could have changes in charge, as well as a total charge, which had to be integer multiples of a single unit of charge. None of this could be determined without actually taking and recording data on a candidate drop. Thus, it should not be surprising that Millikan chose to use the data on only 58 of the drops he observed during the period when he and his apparatus had reached near perfection. Furthermore, he had no special bias in choosing which drops to discard. A modern reanalysis of Millikan's raw data by Allan Franklin (see following page) reveals that his result for the unit of charge and for the limits of uncertainty in the result would barely have changed at all had he made use of all the data he had, rather than just the 58 drops he used.

I don't think that any scientist, having studied Millikan's techniques and procedures for conducting this most demanding and difficult experiment, would fault him in any way for picking out what he considered to be his most dependable measurements in order to arrive at the most accurate possible result. In the 1913 paper, he cites his result with an uncertainty of 0.2 percent, some 15 times better than the best previous measurement (which reported an error of 3 percent). Furthermore, the value of the charge of the electron today agrees with Millikan's result within his cited uncertainty of 0.2 percent. The experiment was nothing less than a masterpiece, and the 1913 paper reporting it is a classic of scientific exposition. Nevertheless, it contains the phrase "this is not a selected group of drops, but represents all the drops experimented upon during 60 consecutive days," which is manifestly untrue. The question is, why did Millikan mar his masterpiece with a statement that clearly is not true?

Many years after the fact, Millikan's work was studied by historian Gerald Holton, who told the story of the Millikan-Ehrenhaft dispute ("Subelectrons, Presuppositions, and the Millikan-Ehrenhaft Dispute," in *Historical Studies in the Physical Sciences*, 1981) and contrasted Millikan's published results with what he found in Millikan's laboratory notebooks. Holton did not accuse Millikan of misconduct of any kind, but instead found in the unpublished laboratory notebooks an



Allan Franklin's reanalysis of Millikan's observations on published (solid) and unpublished (open) oil drops demonstrates that the scatter in his results lessened over time. Shown here are estimates of *e* derived from all the drops for which Millikan obtained adequate data after February 13, 1912, the day he gathered observations on the first of the 58 drops he ultimately published. Millikan was clearly being selective, but his choice of drops did not bias the overall result.

opportunity to contrast a scientist's public, published behavior with what went on in the privacy of the laboratory. Holton's work was seized upon by two journalists, William Broad and Nicholas Wade, who in 1982 published a book about misconduct in science called *Betrayers of the Truth*. Broad and Wade, both of whom were then reporters for *Science* magazine, and both of whom now write for the *New York Times*, are the ones who tried and convicted Robert Millikan of scientific misconduct. Others, like the writer of Sigma Xi's *Honor in Science,* simply bought their argument at face value.

In *Betrayers of the Truth*, Broad and Wade want to make the point that scientists cheat. Chapter 2, "Deceit in History," starts out with a list of culprits: Claudius Ptolemy, Galileo Galilei, Isaac Newton, John Dalton, Gregor Mendel, and Robert Millikan. At the very least, Millikan is in good company. Of Millikan they say he "extensively misrepresented his work in order to make his experimental results seem more convincing than was in fact the case."

Every revision of his technique, every improvement of his apparatus, every word he wrote, public or private, was directed toward one goal only: the most accurate possible measurement of the charge of the electron.

I would argue that this statement is profoundly incorrect. (The accusations against most of the other scientists on the list are equally spurious—see "Scientific Fraud," *E&S*, Winter 1991.)

For the statement by Broad and Wade to make sense, Millikan's principal experimental result would have to be that there exists a smallest unit of electric charge. We would have to imagine that the existence of electrons, and by implication, the existence of atoms, was an issue of burning controversy in 1913, with Millikan on one side and Ehrenhaft on the other, and that the whole point of Millikan's exercise was to prove that "subelectrons" did not exist. In fact, there were in 1913 a small number of respectable scientists who still insisted that the existence of unseen atoms was an unnecessary and unscientific hypothesis, but they had by then been left far behind by the mainstream of science, and besides, even they would not have chosen Ehrenhaft as their champion. To Millikan, who had seen Brownian motion with his own eyes, the existence of atoms and electrons was beyond question. Every revision of his technique, every improvement of his apparatus, every word he wrote, public or private, was directed toward one goal only: the most accurate possible measurement of the charge of the electron. Ehrenhaft and the supposed controversy are never so much as mentioned. And it is worth remembering that history has vindicated Millikan in that his result is still regarded as correct. Nevertheless, we are still stuck with the blatantly false statement, "[A]ll the drops experimented upon during 60 consecutive days."

To understand the significance of that statement, I must make a small digression. Millikan's oil drops rose and fell under the influence of three countervailing forces: gravity, electricity, and viscosity. The first two of these were very well understood. For the third, the 19th-century hydrodynamicist George Stokes had produced an exact formula applicable to a sphere moving slowly through an infinite, continuous viscous medium. The conditions that would make Stokes's law exact were well-satisfied by Millikan's oil drops in all respects except one: the drops were so small that the air through which they moved could not safely be considered a continuous medium. Instead, the air was made up of molecules, and the average distance between molecules was not completely negligible compared to the size of an oil drop. For this reason, Stokes's law could not be depended on as absolutely correct.

To deal with this problem, Millikan assumed, entirely without theoretical basis, as he stressed in his paper, that Stokes's law could be adequately corrected by an unknown term that was strictly proportional to the ratio of the distance between air molecules to the size of the drop, so long as that ratio was reasonably small. To test this idea, he purposely made that damaging ratio larger than it had to be by pumping some of the air out of his experimental chamber. That is the reason he recorded such low pressure in the page from his notebook dated March 14, 1912. Then, when he had assembled all of his data, he used a trick that would be appreciated by any experimentalist. He plotted a graph of all his data in such a way that, if his supposition was correct, all the data points would fall on a single straight line, and the position of the line on the graph would give the magnitude of the unknown correction term. Thus, if it were successful, this procedure would all at once prove that the proposed method of correcting Stokes's law was justified, and give the magnitude of the necessary correction. In other words, this procedure, like everything else in this experiment, was designed not to question whether charge came in units, but rather to measure the unit of charge with the greatest possible accuracy.

Now let's turn to Millikan's actual published paper. It begins on page 109 of Volume II, No. 2, of the *Physical Review*. He explains how the experiment is done and (with specific drops as examples) how he analyzes his data, using changes in the charge on a drop to help determine the total number of units of charge on the drop. Then, on page 133, he writes: "Table XX contains a complete summary of the results obtained on all of the 58 different drops upon which complete series of observations were made during a period of 60 consecutive days." As we have already seen, his published results came from measurements made over a period of 63, not 60 days, but I think we can forgive him that lapse. The clear implication of the sentence is that there were only 58 drops for which the data were complete enough to be included in the analysis.

Page 133 is followed by two pages of Table XX, and an additional two pages of the graph of the straight-line test of the correction to Stokes's law described above. On page 138, Millikan discusses his test of his presumed correction to Stokes's law. He points out that all of the points do indeed fall on the line, and in fact, "there is but one drop in the 58 whose departure from the line amounts to as much as 0.5 percent." And then, the very next sentence is, "It is to be remarked, too, that this is not a selected group of drops, but represents all the drops experimented upon during 60 consecutive days . . ." The damning remark is made, not in regard to whether charge comes in units, but in regard to getting the correction to Stokes's law right. What he means to say is, "Every one of those 58 drops I told you about confirms my presumed formula for correcting Stokes's law." And, although in *Physical Review* it comes five pages after the remark that qualified the choice of those 58 drops, the intervening pages are tables and graphs. In the typescript submitted by Millikan (which does not survive, to my knowledge) it would have followed almost immediately after the qualifying statement. Thus a careful reading of the context of Millikan's words greatly diminishes their apparent significance as evidence of misconduct.

In fairness, it should be pointed out that, when Millikan published his book *The Electron* in 1917, he did take the trouble to confront Ehrenhaft explicitly and to demolish Ehrenhaft's arguments

Cosmic rays were the subject of Millikan's research in the latter half of his career, after coming to Caltech in 1921 at the age of 53. Not only did he give them their name and call attention to their significance, he also lugged detectors such as this one to various altitudes around the world to measure the rays. Millikan died in 1953.

I believe, after reading *The Electron*, that Millikan's real rival was never the hapless Ehrenhaft, but rather J. J. Thomson—not because they disagreed scientifically, but because both wanted to be remembered in history as the father of the electron.

very effectively. He also used verbatim the section of his 1913 paper on Stokes's law, thus repeating the offending assertion of having used every drop, without the earlier qualifying statement. Most probably by 1917, he had forgotten the very existence of the other drops he had observed, however incompletely, between February and April of 1912. I believe, after reading *The Electron*, that Millikan's real rival was never the hapless Ehrenhaft, but rather J. J. Thomson—not because they disagreed scientifically, but because both wanted to be remembered in history as the father of the electron.

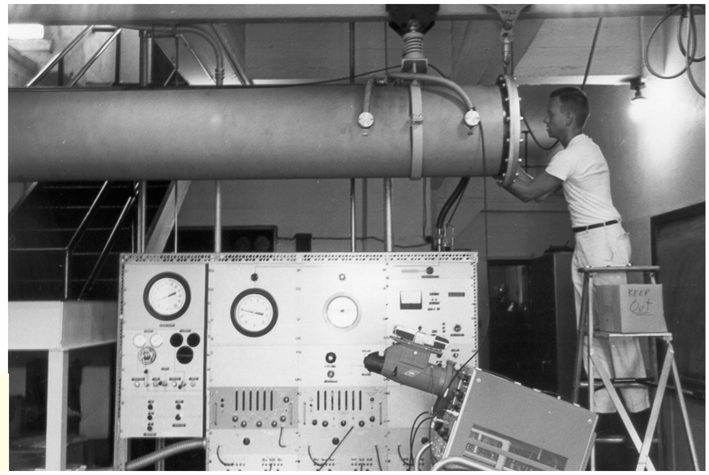
In recent times, Millikan has become a juicy target for certain historians because he was very much a part of the establishment, as well as being white and male, and, of course, he is no longer here to defend himself (I'm trying to fill in on that last point). For example, there is a letter, noted in feminist circles, in which Millikan advised the president of Duke University not to hire a female professor of physics. This occurs much later, in 1936, and Millikan is now the famous and powerful head of the California Institute of Technology. W. P. Few, Duke's president, had written to Millikan in confidence, asking his advice on this delicate issue. Millikan's reply shows his unease: "I scarcely know how to reply to your letter. . . ." he begins. "Women have done altogether outstanding work and are now in the front rank of scientists in the fields of biology and somewhat in the fields of chemistry and even astronomy," Millikan writes later, "but we have developed in this country as yet no outstanding women physicists." He points out that "Fräulein Meitner in Berlin and Madame Curie in Paris" are among the world's best physicists, but that's Europe, not the U.S. "I should therefore," he concludes his confidential advice, "expect to go farther in influence and get more for my expenditure if in introducing young blood into the department of physics I picked one or two of the most outstanding younger men, rather than if I filled one of my openings with a woman."

In his private correspondence, Millikan also reveals an attitude toward Jews that would not be acceptable today. For example (as noted in *Millikan's School* by Judith R. Goodstein), writing from Europe to his wife, Greta, he describes physicist Paul Ehrenfest (not to be confused with Felix Ehrenhaft) as "a Polish or Hungarian Jew [Ehrenfest was, in fact, Austrian] with a very short, stocky figure, broad shoulders and absolutely no neck. His suavity and ingratiating manner are a bit Hebraic (unfortunately) and to be fair, perhaps I ought to say too that his genial open-mindedness, extraordinarily quick perception and air of universal interest are also characteristic of his race."

What are we to make of these lapses? They are certainly not the rantings of a mindless bigot. Undoubtedly Millikan's biases were typical at the time of a man of his upbringing and background. It should be said that, regardless of whatever prejudices he harbored, they never interfered with his judgment of scientists. His hero A. A. Michelson was Jewish, as were many of the stars Millikan personally recruited to Caltech: Paul Epstein, Albert Einstein, Theodore von Kármán, and Beno Gutenberg among others. Such actions demonstrate that Millikan's personality was more complex than his detractors acknowledge. Like anyone, he had his strengths and his flaws. He wasn't generous enough to put his student's interests ahead of his own at a critical point in his career. In describing the results of his oil-drop experiment, he let himself get carried away a bit in demonstrating the correctness of his empirical correction to Stokes's law. And his words about women and Jews grate on modern sensibilities. But Robert Andrews Millikan was not a villain. And he certainly did not commit scientific fraud in his seminal work on the charge of the electron.

Ladies and gentlemen, the defense rests. □

David Goodstein, professor of physics and applied physics, the Frank J. Gilloon Distinguished Teaching and Service Professor, and vice provost, has, he claims, the longest title at Caltech and possibly in all of academia. He has also been a member of the faculty a rather long time, having joined it in 1966 after receiving his PhD from the University of Washington. Although his own research has been in low-temperature physics, Goodstein has been a loyal author for E&S *over the last couple of decades on topics ranging from scientific fraud to superconductivity to the excess supply of PhDs, as well as contributing numerous book reviews.* E&S *hasn't always been the primary recipient, as is the case with this article, which is adapted from an address to the 2000 Sigma Xi Forum, "New Ethical Challenges in Science and Technology," in November, where he received Sigma Xi's John P. McGovern Science and Society Award. The lecture was first published in the January–February 2001 issue of* American Scientist.



Sturtevant with GALCIT's 17-inch shock tube in the early 1960s.

Brad Sturtevant
1933 – 2000

"Brad made a magical connection, not only between aeronautical engineering and geology and geophysics, but between engineering and science."

Bradford (Brad) Sturtevant, the Hans W. Liepmann Professor of Aeronautics, died October 20, of pancreatic cancer at the age of 66.

Arriving at Caltech as a graduate student in 1955, with a bachelor's in engineering from Yale, Sturtevant earned his PhD in 1960 and stayed on at GALCIT (Caltech's Graduate Aeronautical Laboratory) for the rest of his career. He was preceded by his great uncle, Alfred Sturtevant, who, with Thomas Hunt Morgan, was among the founders of the Division of Biology in 1928. But while the elder Sturtevant studied the genetics of fruit flies (and irises), Brad's research was in fluid dynamics, particularly shock waves and nonsteady gas dynamics. He was named associate professor in 1966, full professor in 1971, and appointed to the Liepmann chair in 1995.

A memorial gathering in remembrance and celebration of Sturtevant's life was held Saturday, February 24, following a reception and buffet and Scott Joplin piano music. Hans Hornung, the C. L. "Kelly" Johnson Professor of Aeronautics and director of GALCIT, surveyed the large crowd in Dabney Lounge and declared that if Sturtevant could see this, he would say, "'Why don't you all go back to your labs and do an honest day's work?'" (Sturtevant was well known for working on Saturdays.) But everyone stayed, and the memorial continued.

Victoria Sturtevant stated three things she had learned from her father: "If it hurts, it's good for you"; "think about it and work it in your head to figure out how it works before you break it"; and "choose a career where you'll constantly learn." Brad Sturtevant took these tenets extremely seriously himself, as his colleagues, students, and friends proceeded to attest.

Hans Liepmann, the Theodore von Kármán Professor of Aeronautics, Emeritus, and former GALCIT director, recalled Sturtevant's style in designing experiments: "very prepared. He thought he could design an experiment that would work the first time," whereas others, including Liepmann, had a different approach: "We would first do it lousy and then a little better and then a little better."

Liepmann noted that Sturtevant exemplified GALCIT's mission: "We do not want to produce specialists but we want to produce people who can specialize wherever they want to." From the molecular beam that he built for his PhD thesis under Liepmann, Sturtevant became interested in kinetic theory and then in shock wave structure. He went on to apply his shock wave research to motorcycle noise and sonic booms and to fields as disparate as geology and medicine. With Hornung, he built the T5 Hypervelocity Shock Tunnel in 1988. Hornung joked that, throughout construction, "Brad wanted everything to be done *right*," even the cleaning up. (A slide showed Sturtevant directing his boss at the vacuum cleaner.)

Representing colleagues from the Indiana University School of Medicine, Andy Evan spoke of Sturtevant's work with a group interested in shock wave lithotripsy. The Indiana group had met him in 1988, when both were seeking other investigators. "Brad was very interested in how shock waves break up kidney stones," said Evan. "We were interested in how shock waves caused damage to tissue. It seemed a perfect match for collaboration." Despite initial disappointment in attracting NIH funding, it was Brad's optimism and contagious enthusiasm that kept the project going, said Evan. "I don't need to remind you how

incredibly bright Brad really was, how gifted he was at analysis, and what a fertile flow of original ideas he generated."

His forays into volcanology were described by geologist Sue Kieffer, PhD '71, who, although she had audited one of Sturtevant's courses, didn't run into him again until Seminar Day 1981, when she gave a talk on the Mount St. Helen's eruption. Sturtevant challenged her conclusions, and the encounter led to a "fruitful collaboration resulting in two papers that proved a number of things about the destructive forces of the supersonic nature of the blast of 1980."

"Brad made a magical connection, not only between aeronautical engineering and geology and geophysics, but between engineering and science," said Kieffer. "Neither of these is a mean feat given the vastly different content and training of the researchers in the different fields."

Interdisciplinary research may have its downside, however. Added Liepmann, "I, for one, firmly believe that it actually reduced the number of Brad's honors and the extent of his support. When it comes to voting for an award, the tendency to keep it within your own narrow group is widespread."

Half of the 28 students who received their PhDs under Sturtevant returned to attend the memorial, some traveling long distances. Several, including Willie Behrens ('66), Martin Brouillette ('85), and Bert Hesselink ('77), offered affectionate reminiscences of the man as adviser—his "enormously high standards" and demanding presence, his energy, enthusiasm, and his insistence on the proper use of the English language (even semicolons). But "the most important thing I learned from Brad is what it is to be a scientist, and I thank him for that," said Brouillette.

Another of those PhD students, Joe Shepherd ('81), professor of aeronautics, who served as master of ceremonies at the memorial and also produced the slide show, said, "We all learned, I believe, an enormous amount from Brad, both on the personal and scientific level." Shepherd also led into Sturtevant's "other life" as a vigorous athlete. "When I described Brad Sturtevant to the local newspaper recently," said Shepherd, "I found that I had almost completely omitted the fact that he was also a scientist, and so the headline came out that he was a 'sportsman.'" His "perfectly healthy" life was regarded with awe. "On one thing I disagree with him after the fact," said Liepmann. "He died so early; you probably should not believe in doing everything to remain healthy."

But health wasn't what it was all about. "He loved the mountains and the oceans and everything outdoors," said Anatol Roshko (PhD '52), the Theodore von Kármán Professor of Aeronautics, Emeritus. Roshko described and showed slides of a 1957 hike in the Sierra to the Ionian Basin, which illustrated Sturtevant's penchant for planning and organization. "Along the way, he seemed to know every feature, every elevation, every contour, and the hike worked out exactly the way he planned it," said Roshko. "Whatever he undertook, whether it was in his science, or swimming, or hiking, or whatever, he did it all thoroughly."

He had hiked and sailed since boyhood, and when he came to California, he also took up surfing. In the '60s, he and his wife, Carol, whom he had met at the Caltech pool, "bought a boat instead of a house" and competed in many ocean sailing races together.

Sturtevant was especially renowned for swimming, open-water swimming races in particular, for which he won numerous prizes and honors. He was a regular lap swimmer at the Caltech pool as well. During the early '80s, he worked out three times a day, said Michael Hoffmann, the James Irvine Professor of Environmental Science and a fellow member of the faculty athletic committee for many years. "He swam in the morning, lifted weights and ran at noontime, and then swam again in the evening. And each workout lasted 90 minutes or so. He also would brag that up until about two years ago, every year he bested his benchmark time from his days on the Yale swim team, which is a remarkable accomplishment." But Hoffmann punctured the image of Sturtevant's perfectly healthy life: "I used to see him in the morning after his workouts, eating doughnuts over at the Greasy."

And he drank wine too, said Tim Downes, director of athletics, who was pleased to see that wine was served at the memorial buffet. "Some of my fondest memories of Brad are of sitting next to him at endless athletic conference meetings after we had had a couple of glasses of wine," said Downes. Sturtevant, as well as Hoffmann and Downes, represented Caltech over the years at the Southern California Intercollegiate Athletic Conference; Sturtevant also served several terms as chairman.

He was also a key figure in the planning and construction of the Braun Athletic Center. And when that was completed, he "re-upped for a second tour of duty," on the Sherman Fairchild Library of Engineering and Applied Science, according to Kimberly Douglas, director of that library. "He was not a limelight guy; his name does not appear in the library nor on the gym," said Douglas, but "these buildings are certainly testimony to his willingness to give up his time and considerable talent to make the Institute a better place for all." Added Shepherd, "He had a profound sense of responsibility to the community here at Caltech."

While Sturtevant's colleagues, friends, and students had described him as exacting, rigorous, creative, imaginative, energetic, competitive, intense, and great fun, the Rev. Douglas Vest, his next-door neighbor in Rubio Canyon for 25 years, thought one attribute had been left out. He remembered "the tender side of Brad." When he left the house at 5 a.m. for the pool, he would roll his car down the hill before turning on the ignition so as not to wake the neighbors. Vest, who ended the program, also told of sitting in silence with his longtime neighbor last summer after his disease had been diagnosed, "and I realized he was comfortable about his life; he was comfortable about his family; he was comfortable about the unknown."

An intercollegiate varsity swimming award has been established in Sturtevant's honor, but, like his great uncle, he will also have a physical tribute on campus that is uniquely associated with his life at Caltech. The iris garden north of Gates Annex, planted in memory of Alfred Sturtevant, is populated with descendants of the irises he bred in his later genetic studies. In Brad Sturtevant's memory, a Jacuzzi will be constructed at Braun Athletic Center so that "he will always have a place on the pool deck." □

J. Harold Wayland
1909 – 2000

"Harold was a great man in applying classical physics to biology. He had a vision of the new field of bioengineering long before the word was coined."

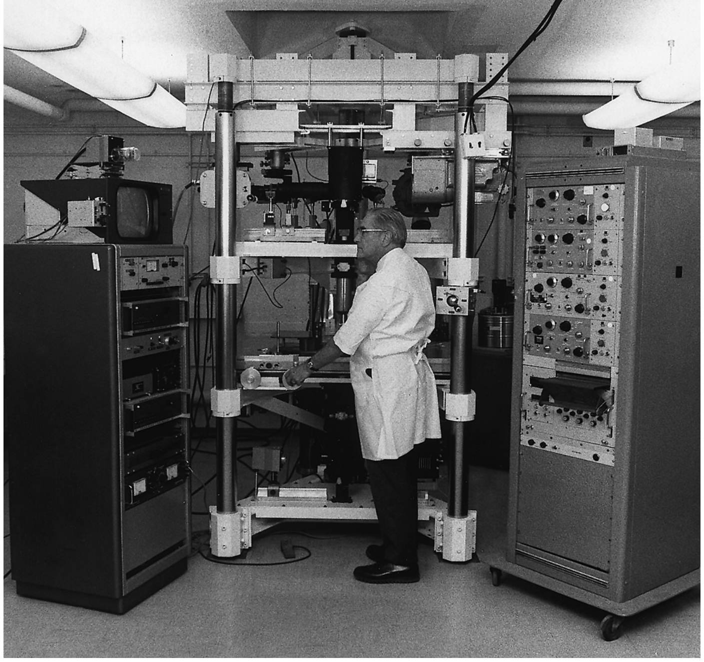
J. Harold Wayland, professor of engineering science, emeritus, and a pioneer of bioengineering, died October 10, 2000, at the age of 91. At a memorial service held January 29 in Dabney Lounge, friends and colleagues remembered his contributions to science and to the Caltech community.

Wayland's long membership in that community dates back to 1931, when he arrived at Caltech as a graduate student after earning his BS from the University of Idaho. He earned his MS in 1935 and his PhD in physics and mathematics in 1937—with Robert A. Millikan as his thesis adviser, according to George Housner, the Braun Professor of Engineering, Emeritus, who spoke of his 50-year-long friendship with Wayland.

Bill Pickering had known him even longer. Pickering, professor of electrical engineering, emeritus, and former director of the Jet Propulsion Laboratory, met Wayland in the mid '30s, when both were graduate students. "If I remember rightly, I think the first time I met Harold was on the trail to Mount Baldy, when we were doing what young graduate students frequently did—exploring the local mountains," said Pickering. Their two families remained close over the following decades, and Pickering recalled fondly a visit to the Waylands in Strasbourg in 1953. "They started the tradition of globetrotting very early."

As early as 1936, in fact, when Wayland left for a year's fellowship to Niels Bohr's Institute for Theoretical Physics in Copenhagen. Then, after a year as assistant professor of physics at the University of Redlands, he returned to Caltech as a research fellow from 1938 to 1941. He spent the years 1941–1944 degaussing ships for the Navy in Long Beach, and then joined Caltech's project for the Navy's Underwater Ordnance Division, where he was involved with other Caltech faculty in designing the torpedo launcher at Morris Dam.

In 1949, he returned permanently to academia as associate professor of applied mechanics at Caltech. He



With his microscope (at one time referred to as a "megascope"), Wayland, shown here in 1971, could observe blood flow in a living animal's tinest blood vessels.

was named full professor in 1957, professor of engineering science in 1963, and retired as emeritus professor in 1979.

From the early '50s, Wayland studied streaming birefringence, or double refraction, as a means of visualizing complex fluid flows, in particular large molecules in fluids. When Wallace Frasher and Sidney Sobin started a cardiovascular research laboratory, specializing in small blood vessels, at USC's medical school in 1957, they looked around Los Angeles for some assistance in mathematics and physics. They found no one at USC or UCLA, "so we looked up the hill to Caltech," recalled Sobin. "I knew one person here, told him we wanted someone from the physical sciences who would work with us. He said, 'Your man's Harold Wayland.'"

So Wayland, working with Frasher and Sobin, began to focus on microcirculation, the flow of blood through the tiny capillaries. Wayland supplied the knowledge of optics, mathematics, engineering, and fluid dynamics. His particular contribution was in devising quantitative methods and building instruments to observe and measure blood flow in living animals. To accomplish this, he built a huge microscope, seven and a half feet tall, weighing a couple of tons ("big enough to hold a goat," according to Sobin). Wayland also conducted research on the impact of diabetes mellitus on blood flow and on the molecular exchanges between blood and tissues that occur at the level of the smallest vessels in the body.

In the early '60s, a Caltech aeronautics professor, Yuan-Cheng Bertram Fung (PhD '48), became interested in the possibilities of analyzing the forces and stresses of the human body as thoroughly as those of airplanes, and joined the group working on microcirculation. In 1966, Fung left for UC San Diego, where he subsequently laid the framework for the new field of bioengineering. Many of the original Caltech group joined him, including Sobin, now professor of bioengineering, emeritus, at UCSD, who credits Wayland with starting the spin-off. In December 2000, Fung was awarded the National Medal of Science. (See *Caltech News*, No. 4, 2000.)

"Harold was a great man in applying classical physics to biology," said Fung at the memorial service. "He had a vision of the new field of bioengineering long before the word was coined, and he was evangelical in bringing the message of the importance of physical optics to biology and medicine." Taking his cue from George Ellery Hale, said Fung, Wayland preached the establishment of international "intravital observatories," which would do for biology what Mount Wilson and Palomar had done for astronomy. This may be Wayland's greatest legacy, claimed Fung. "I think the idea is still alive and will probably wait for future people to come"—most likely in Japan and China, where Wayland had many "disciples" and was very well known, according to Fung.

In later years Wayland's work was recognized at home and abroad. The U.S. Microcirculatory Society gave him its highest honor, the Landis Award, in 1981. And in 1988, he was awarded the Malpighi Award of the European Society for Microcirculation (Malpighi, in 17th-century Italy, was the first to observe blood cells in capillaries through a microscope). The gold Malpighi medal was presented to him at the University of Maastricht, which Wayland had helped develop into one of the leading institutions in the world for studies of microcirculation.

Two other professors of bioengineering at UC San Diego also remarked on their early experience working with Wayland. Paul Johnson, now emeritus, came to Caltech for a year in 1965 to work on developing quantitative techniques for measuring blood flow. "Harold had an enormous influence on my life and career. But I think what I've described in my own experience you could duplicate for dozens of other people who came and spent time in his laboratory. He was absolutely focused on making the very best research experience for anyone who came to work with him."

And Marcos Intaglietta, PhD '63, who was a student of Wayland's, noted that, "in my cosmology Harold remains the archetype of the professor. He is a rigorous person, unyielding on principles, but vastly human in education and hospitality." Intaglietta also remarked on Wayland's vision: "He envisioned the contribution that engineering was poised to make in the life sciences and acted upon it. . . .His laboratory became the host to technicians and physiologists, a pioneering initiative when 'interdisciplinary' was not a household word. . . . He saw the future and caused it to start."

Many of the memorial speakers commented on Wayland's enthusiasm for his work and for his many interests outside the lab, especially music and the history of playing cards, on which he and his wife, Virginia, wrote several books. Ward Whaling, Caltech professor of physics, emeritus, described another enthusiasm of his: "On this campus, Harold was known first and foremost for his interest in food and wine." Back in the early '60s, when the Athenaeum had no bar, recounted

Whaling, and the dining room served plain, inexpensive food to postdocs and grad students, Wayland recruited the manager, trained as a chef in France, to collaborate on elegant, "private" dinners, for which Wayland would bring the wines, pour them, and discuss them. He had become a connoisseur of wine on his early jaunts to Europe and had struck up acquaintance with some of the patriarchs of the California wine industry. Other members of the group, called the Apicians, soon began to take turns planning "private" dinners. "And that," said Whaling, who along with his wife was one of the original members, "is the way fine food and wine first made its way into the Athenaeum, which is now judged to be one of the most elegant dining rooms in Pasadena. I think Harold would count that as one of his worthy accomplishments, and one that his colleagues recognize as a notable contribution to the campus."

Virginia Wayland died January 7, 2001, and on January 26, Whaling and Noel Corngold, professor of applied physics, organized one last Apicians dinner (there had been 146 of them in all) in honor of Harold and Virginia Wayland. □

Professor of Political Science Jeffrey Scot Banks, PhD '86, died of complications of a bone marrow transplant on December 21. He was 42. A memorial service will be held April 7 at 3 p.m. in Dabney Lounge. Excerpts from that service will appear in the next E&S.

Honors and Awards

Clarence Allen, professor of geology and geophysics, emeritus, has been selected to receive the 2001 George W. Housner Medal, awarded at the annual Earthquake Engineering Research Institute meeting, February 9, in Monterey, California. The award recognizes his "sustained and significant contributions to earthquake safety."

Tom Apostol, professor of mathematics, emeritus, has been elected a corresponding member of the Academy of Athens. The academy is the most prestigious scientific organization in Greece.

Frances H. Arnold, Dick and Barbara Dickinson Professor of Chemical Engineering and Biochemistry, has been elected a fellow of the American Institute for Medical and Biological Engineering.

David Baltimore, president of Caltech, has been awarded the 2000 Warren Alpert Foundation Prize for his work "in the development of Abl kinase inhibitors for use in the treatment of chronic myelogenous leukemia." Baltimore will share the $150,000 prize with four other scientists.

Seymour Benzer, Boswell Professor of Neuroscience, Emeritus, has received the International Prize for Biology. Awarded annually since 1985 by the Committee on the International Prize for Biology, the prize was presented to Benzer on November 26 at the Japan Academy, in the presence of the emperor and empress.

Michael Brown, assistant professor of planetary astronomy, has been selected by the American Astronomical Society's Division for Planetary Sciences to receive the Harold C. Urey Prize in Planetary Science.

Richard Ellis, professor of astronomy and director of Palomar Observatory, has been appointed the Lansdowne Lecturer at the University of Victoria, Canada. He will deliver three lectures there later in the year.

Sunil Golwala, Millikan Postdoctoral Scholar, has received the American Physical Society's Mitsuyoshi Tanaka Dissertation Award in Experimental Particle Physics "for his versatile and extensive contributions to the detectors, hardware, electronics, software, and analysis of the results of the Cryogenic Dark Matter Search (CDMS) experiment."

Sossina Haile, assistant professor of materials science, has been selected to receive the American Ceramic Society's 2001 Robert L. Coble Award for Young Scholars.

Janet Hering, associate professor of environmental engineering science, has received a grant of $100,000 from the Alice C. Tyler Perpetual Trust. The grant will fund Hering's project, "Environmental Quality Near Large Urban Areas," which will examine the effects of a growing population and the impact of human interaction on land and aquatic ecosystems in the San Gabriel Valley and San Gabriel River watershed.

Alice Huang, senior councilor for external relations and faculty associate in biology, has been selected to receive the 2001 Alice C. Evans Award, which is sponsored by the ASM (American Society for Microbiology) Committee on the Status of Women in Microbiology.

Tracy Johnson, postdoctoral scholar in biology, will be honored at the Roy Campanella Humanitarian Award Dinner, on March 29 at the Pasadena Hilton Hotel. The award honors "outstanding leaders who have distinguished themselves in their fields."

Jonas Peters, assistant professor of chemistry, is one of 59 young researchers named by President Clinton as a recipient of the Presidential Early Career Award for Scientists and Engineers.

Stephen Quake, associate professor of applied physics has been named one of the "Technology Review Ten" by MIT's *Technology Review* magazine for his innovative work in the branch of biotechnology known as microfluidics, which involves manipulating amounts of liquid thousands of times smaller than a drop of water, and which may make possible the automation of genomic and pharmaceutical experiments, the performance of diagnostic tests, or the building of drug-delivery devices, all on mass-produced chips.

Steven Quartz, assistant professor of philosophy, has been selected by the National Science Foundation for a Faculty Early Career Development (CAREER) award, the NSF's most prestigious award for outstanding faculty early in their independent professional careers. Quartz will be funded for five years for his research into the mechanisms of cognitive development, enabling him to construct a computational/robotics framework for exploring how the mind emerges from a developing brain's interaction with environmental complexity.

Anneila Sargent, professor of astronomy and director of both the Owens Valley Radio Observatory and the Interferometry Science Center, has been honored with two invitations, one to be the University of Edinburgh Science Festival Lecturer for 2001, the other to be the Philips Visitor at Haverford College for spring 2001.

Wallace Sargent, Bowen Professor of Astronomy, has been awarded the Henry Norris Russell Lectureship for 2001 by the American Astronomical Society. The lectureship is the society's "most prestigious prize and is awarded annually to recognize a lifetime of preeminence in astronomical research."

Paul Sternberg, professor of biology, who is also an investigator for the Howard Hughes Medical Institute, has been elected a fellow of the American Academy of Arts and Sciences.

Ersan Üstündag, assistant professor of materials science, has also been selected by the National Science Foundation for a Faculty Early Career Development (CAREER) award. The award supports his research into solid-state reactions and phase transformations in materials, particularly ceramics, and the mechanical behavior of materials, especially composites.

Alison Winter, associate professor of history, has been selected to receive the Northeast Victorian Studies Association (NVSA) Sonya Rudikoff Award for her book, *Mesmerized: Powers of Mind in Victorian Britain*. Given for the best Victorian book by a first-time author, the award will be presented in April at the NVSA conference at Brown University.

Peter Wyllie, professor of geology, emeritus, has been selected by the Mineralogical Society of America as the Roebling Medalist for 2001. The Roebling Medal is the society's highest award "for scientific eminence as represented primarily by scientific publication of outstanding original research in mineralogy."

Nai-Chang Yeh, professer of physics, has been awarded the Achievement Award by the Chinese-American Faculty Association of Southern California "for her outstanding contributions to experimental condensed matter physics, particularly in the areas of high-temperature superconductivity and state-of-the-art frequency standards." She was also elected a Fellow of the Institute of Physics with the title of Chartered Physicist. □

Stevenson Wins Feynman Prize

David J. Stevenson, the George Van Osdol Professor of Planetary Science, has been awarded the 2000–2001 Richard P. Feynman Prize for Excellence in Teaching. The prize, made possible by an endowment established by Ione and Robert E. Paradise, is awarded annually "to a professor who demonstrates, in the broadest sense, unusual ability, creativity, and innovation in undergraduate and graduate classroom and laboratory teaching." It carries a cash award of $3,000 and is matched by an equivalent raise in the winner's annual salary. The selection committee detailed the reasons for its choice in the following citation:

"Dave Stevenson chaired the faculty committee that implemented the revised core curriculum, and then seized the opportunity to start a new menu course in Earth and Environment, which embodies the spirit and ideals of the new core. His success in achieving this goal can be measured in part by the remarkable increase in enrollment, which has risen from 20 students at the start to 165 this year. Dave's lucid and enthusiastic teaching style excites student interest, his class notes and supplemental materials provide additional clarity and depth, and his bringing together of concepts from evolution, chemistry, and geology make Geology 1 unlike any other course of its kind in the world. The innovative structure of this course also involves small group projects with individual professors as well as field trips for first-hand observation. This creates a lasting impression of how geology research is done, how our earth was created, and how our environment evolves." □

No, it's not a docking maneuver between an Imperial star destroyer and the Death Star, but a hypothetical solar-sail mission that might one day "shadow" an asteroid in its orbit and observe it indefinitely. A sunlight-propelled spacecraft could fly to the asteroid belt and beyond in less time, stay longer, and carry a larger payload than one using chemical fuel. See the story beginning on page 18. Rendering by Tom Hames.

Engineering & Science

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