California Institute of Technology

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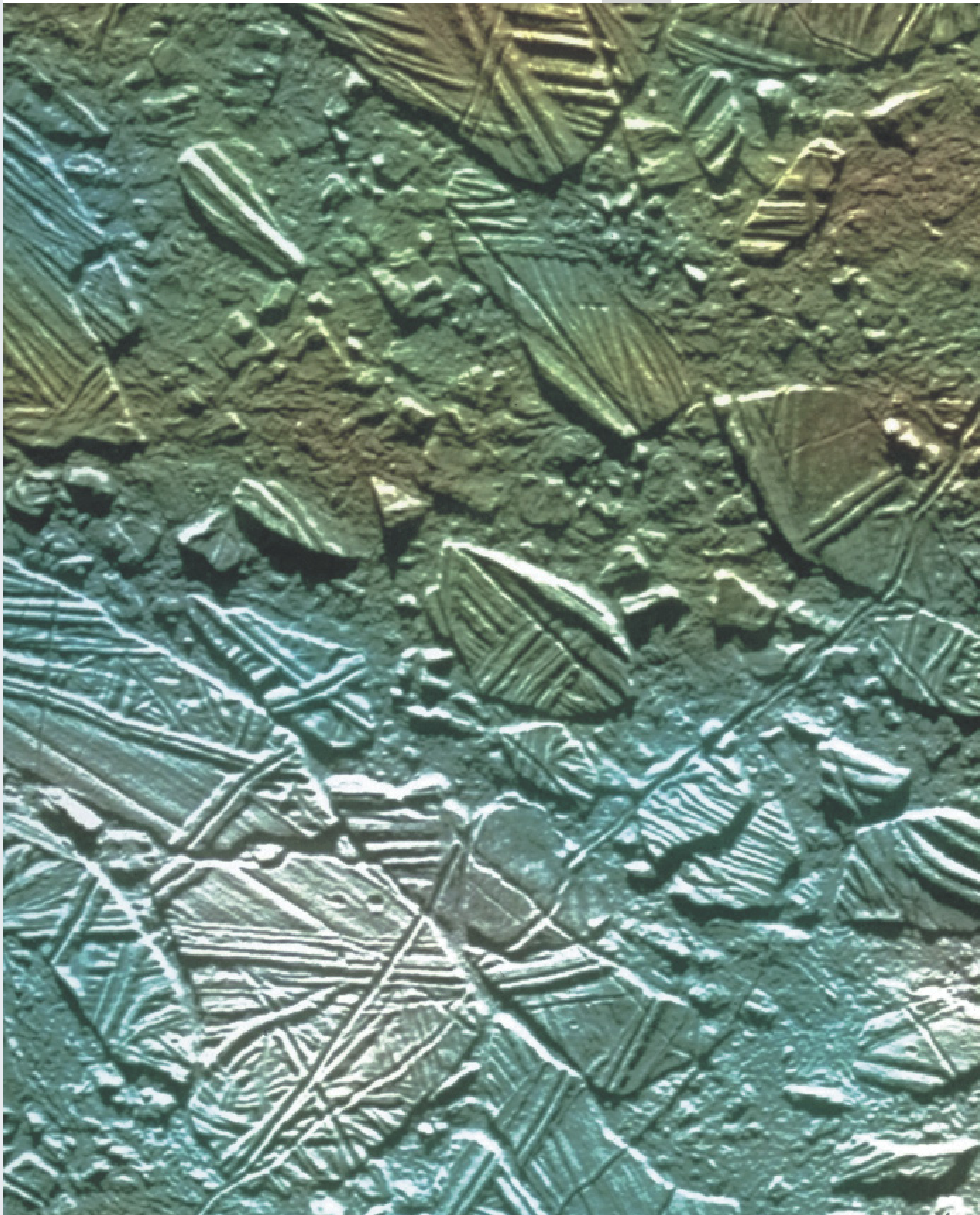

In this issue

Planetary Exploration

Cellular Replication

Coastal Devastation

Nothing stops a tsunami—certainly not glorified sandbars like these, which separate the Bismarck Sea from the Sissano Lagoon on the north coast of Papua New Guinea. (For scale, the lagoon's mouth is about 200 meters wide.) Unfortunately, these spits were the site of several villages, which were washed away like yesterday's sand castles when a tsunami came through on July 17, 1998. The lengthwise stripe down the left peninsula is the scrubbed-bare sand where the village of Warapu used to stand. The wave, which was about 10 meters tall and traveling some 15–20 meters per second, left corrugated metal roofs wrapped around trees and not much else. This scene, which was repeated all over the area, was shot in the Sissano villages, which are just out of frame to the left in the upper photo. What does this have to do with Caltech? See the story on page 26.

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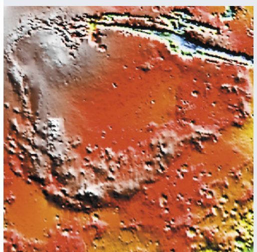

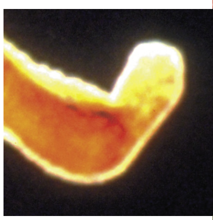

On the cover: The Galileo spacecraft snapped this view of the fractured surface of Jupiter's moon Europa. In this 20-mile-wide swath, huge, blocky ice floes broke loose as the crust flexed, due to tidal forces from Jupiter's gravity. The color-enhanced image shows a blue and white icy surface with patchy reddish-brown deposits of minerals that likely erupted from beneath the crust. Europa is a target of JPL's future missions; see "Sampling the Solar System," beginning on page 8.

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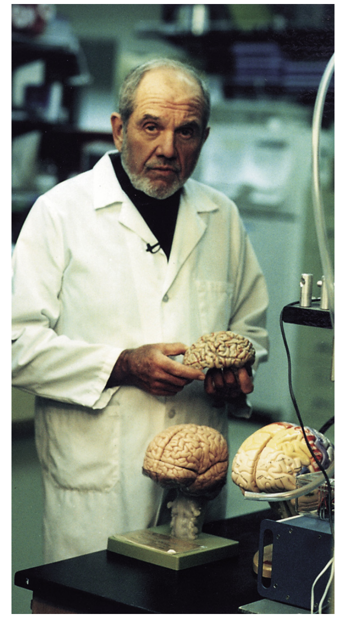
Caltech's Newest Millionaire

At least until the next IPO, Caltech's newest millionaire is Joseph Trela (BS '97), who on March 23 took Regis Philbin all the way on the hit TV quiz show *Who Wants to be a Millionaire?*, becoming only the third contestant ever to have done so. (In case you've been living under a rock, *Millionaire* players answer progressively harder questions to win increasing sums up to $1,000,000.) Contestants are allowed to "Phone A Friend" once during the taping if they get stumped, and, says *The California Tech*, "a mob" of residents of Trela's old house, Dabney, were standing by the lounge phone to take his call. Although the Darbs never made it on the air, Professor of Literature Jenijoy La Belle did when he said that she'd "be very disappointed in him" if he blew the source of the quote, "The first thing we do, let's kill all the lawyers." (He did not let her down, correctly citing *Henry VI, Part II*.) And, fittingly for a Techer, his million-dollar question was to name the insect that shorted out an early supercomputer and inspired the term "computer bug"—moth, roach, fly, or Japanese beetle. (It's a moth.)

So what's he going to do with the money? Oh, the usual—pay off his student loans, put his brother through Notre Dame, take some time off…



Right: The day the episode of *Millionaire* aired, PBS was on campus taping "The College of Comedy with Alan King" for *Great Performances.* (In fact, King thanked the crowd that packed Beckman Auditorium for coming to see him rather than staying home to watch that other show.) In the introductory segment, taped in Rosen Professor of Biology Scott Fraser's lab, King picks his brain before doing his shtick.

Left: Caltech's oldest millionaire, Life Trustee and Chair Emeritus Arnold Beckman (PhD '28), turned 100 on Monday, April 10. The preceding weekend, Caltech's Beckman Institute hosted a symposium highlighting research at the interface of chemistry and biology—a conjoining that Beckman left his mark on. On the day itself, Caltech threw a black-tie gala, including fireworks, in his honor. Here he prepares to blow out the candles on his birthday cake, shaped in the likeness of Beckman Auditorium—one of four buildings on campus to bear the Beckman name—as President Baltimore cheers him on.

In other food-related news, Luke Wang (PhD '97) shot the picture at left at the Universal Studios theme park in Florida. In case you can't read it, the drum says "Home of the BIG ONE." And the canned pork product below, spotted on the shelves of a local grocery store, is the first luncheon meat that also detects gravitational waves. (It's distributed by the Liberty Gold Fruit Company of South San Francisco, hence the name.)

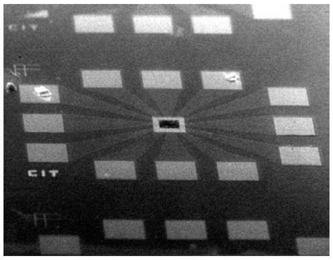
You Can't Beat This Heat

A team led by Professor of Physics Michael Roukes has announced the first observation of the quantum of thermal conductance. This discovery reveals a fundamental limit to the heat that can be conducted by objects of atomic dimensions. The findings, reported in the April 27 issue of *Nature*, could have profound implications for the design of microscopic electronic devices and for the transmission of information, says Roukes.

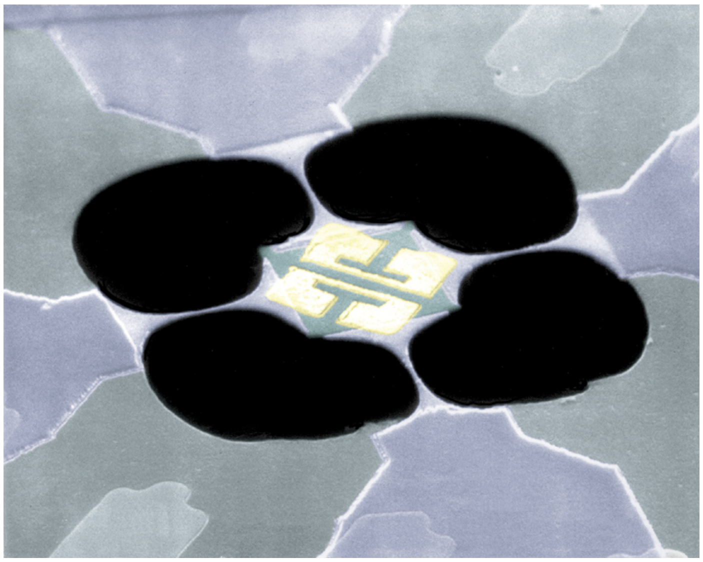
Heat flows through a solid object by means of collective wavelike vibrations of its atoms. These waves are called phonons after the fashion of electrons, protons, photons, etc., but based on the Greek root, *phon*, for sound. Usually immense numbers of phonons, each inducing a unique type of synchronous motion of the atoms, act simultaneously. In the everyday world, each phonon is just one among a sea of zillions—its contribution is imperceptible, and variations in heat flow appear to be smooth and continuous, not incremental.

But in the nanoworld, the phonon sea is finite—more of a pond, really. Quantum effects rule, and heat conduction can become radically different. When an object at temperatures close to absolute zero becomes extremely small, only a limited number of phonons play a significant role in heat flow within it; most types of motion become "frozen out," leaving the heat to be carried by the few modes that persist. Unlike a quantum of light, or photon, which is the minimum package of light energy that can exist, a quantum of thermal conductance is the maximum amount of heat energy that can be carried by a phonon mode. The Roukes team has demonstrated that this conductance depends only on a handful of fundamental physical constants and the absolute temperature itself, regardless of the solid—in other words, at this level, asbestos conducts heat as efficiently as copper. (For the physicists in the audience, the conductance equals $p^2k^2T/3h$, where k is Boltzmann's constant, T is the absolute temperature, and h is Planck's constant. At an ambient temperature of one kelvin, this translates into 9.4×10^{-13} watts of power per kelvin of temperature rise.)

To measure such minute changes, former Sherman Fairchild Distinguished Postdoctoral Scholar Keith Schwab, the *Nature* paper's lead author and now at the National Security Agency and the University of Maryland, fabricated tiny devices with specially patterned features only 100 billionths of a meter across—about 300 atoms wide—with assistance from then-research staff member Erik Henriksen, now at Columbia University, and in collaboration with visiting associate John Worlock of the University of Utah. The group's three-year effort followed on the work of Thomas Tighe, a previous postdoctoral fellow in the



Left: An overall view of the roughly 1.0 × 0.8 millimeter device, showing the 12 wirebond pads that converge, via thin-film niobium leads, into the central 60-nanometer-thick silicon nitride membrane, which appears dark. Below: The suspended 4 × 4 micron "phonon cavity" (center) is patterned from the membrane, which has been completely removed in the dark regions. The bright C-shaped objects on the cavity are the thin-film gold transducers—the "electron puddles"—which are connected to the thin-film niobium leads that run atop the "phonon waveguides" to the wirebond pads. The waveguides neck down to less than 200 nanometers wide.

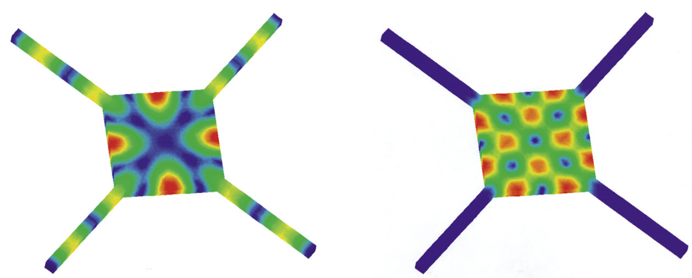


group, and culminated in new techniques for creating the devices out of silicon nitride. At the heart of the device is an isolated heat reservoir, called a "phonon cavity," which is a miniature plate freely suspended by four narrow beams. Each beam acts as a quasi-one-dimensional "phonon waveguide" for heat flow. On top of the cavity, Schwab and Henriksen deposited two thin-film patches of gold, described by Roukes as "puddles of electrons." One puddle is used as a heater; the other as a thermometer. To escape from the suspended cavity, the heat must flow through the waveguides. Meanwhile, the cavity saturates at a higher temperature that directly reflects the waveguides's thermal conductance. (The puddles' electrical leads, which run atop the phonon waveguides, are made of superconducting material since the thermal conductance of an ordinary metal would thermally "short out" the measurements.)

Measuring this temperature rise (typically a few millikelvins at a temperature of 100 millikelvins) was a significant challenge in its own right. Most thermometry techniques involve electrical power levels that would have overwhelmed the measurements. "We used about a femtowatt of power to heat the cavity, which is roughly what your eye would receive from a 100-watt light bulb 60 miles away," says Schwab. So the researchers coupled the second "electron puddle" to extremely sensitive dc-SQUID (superconducting quantum interference device) circuitry that allowed them to measure the feeble current fluctuations whose magnitude is directly proportional to absolute temperature. (This so-called Johnson-Nyquist noise is also the origin of the electrical noise that causes the background hiss in audio systems.) Because the researchers know the precise amount of heat deposited, and can directly measure the absolute temperature reached by the cavity in response, they can calculate the thermal conductance of the waveguides.

Since this conductance is independent of the material, the only way it can be increased in a very small device is to make the conductor larger, which has important implications for nanotechnology as well as for the transmission of information. Each individual transistor on a microchip gives off a little heat, which becomes a significant problem when millions of such transistors are placed in close proximity. "This will become especially serious for future molecular-scale devices," says Roukes. "No matter how small a device is, you always have to put a finite amount of power into it to turn it on. In the quantum regime, when only a limited number of modes are capable of transferring heat, it will be crucial to take this fundamental limitation into account."

Theoretical studies carried out elsewhere indicate that the maximum thermal conductance is linked to the maximum rate that information can flow into a device having a single quantum "channel"—a manifestation of a deep connection between information and entropy. "As we engineer smaller and higher speed computational elements, we will also encounter this fundamental quantum limitation in the rate of information flow," says Schwab. □—*RT*



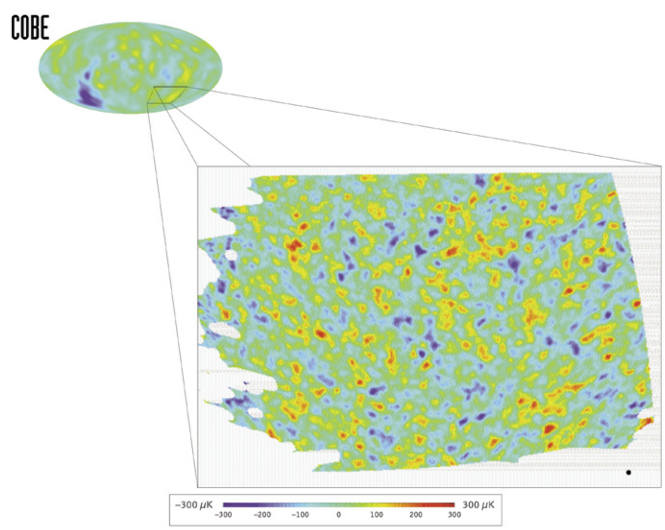
In these simulations of phonon vibrational modes by grad student Darrell Harrington, red represents high local strain amplitude and violet is low. At left is a mode that includes the waveguides and thus allows the cavity to cool. At right is a localized mode in which the waveguides are quiescent (violet) and cannot directly transfer energy to the outside world.

There's an outdoor showcase for experimental art on campus now, tucked in behind the recycling center on Holliston Avenue. The location is particularly apt for the latest work, Economic Icon: Mine Sight, by C. Ian White. The half-buried, gold-wrapped 55-gallon drums are a meditation on the waste our society generates, and a call to Techers to better the planet through their research and their personal lives. Administered by the Institute Art Committee and curated by Dustin Ericksen of Infrared Astronomy and Mike Rogers of Public Relations—both artists themselves—the site opened on October 23, 1999, with an exhibition called Metonym Ocean Size, by Jeremiah Day.

Who Says Columbus Was Right?

From the smallest variations in heat ever observed we move to the oldest—the cover story of the April 27 issue of *Nature* is the late-breaking news that a collaboration of 36 scientists from 16 institutions in four nations, with the U.S. contingent led by Professor of Physics Andrew Lange, has released the first detailed images of the infant universe at a mere 300,000 years old. These images are graven in the so-called cosmic microwave background (CMB), which permeates the universe in all directions and is the fossilized heat from the Big Bang. (Arno Penzias and Robert Wilson (PhD '62) discovered the CMB in 1965, earning them the Nobel Prize in physics in 1978.) Tiny, localized irregularities in the CMB's temperature bespeak subtle density fluctuations in the newborn universe—the seeds of the clusters of galaxies we see today—and their apparent size reveals the universe's shape and foretells its fate. Gross variations in the CMB were first seen in 1991 by NASA's Cosmic Background Explorer (COBE), which surveyed the entire sky but lacked the fine resolution to pick out these features.

Now the BOOMERANG (Balloon Observations of Millimetric Extragalactic Radiation and Geophysics) project has looked at roughly 2.5 percent of the sky with an angular resolution 35

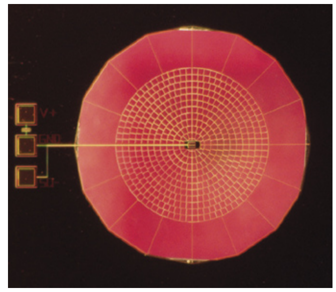


The BOOMERANG (bottom) and COBE data. For scale, the black circle at lower right is half a degree in diameter—the size of the full moon.

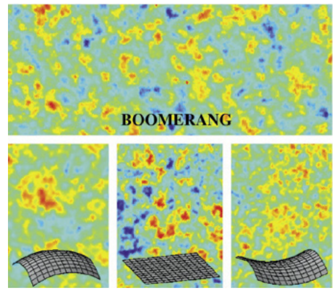
times that of COBE, detecting a complex pattern of temperature variations, typically of only 100 millionths of a degree (0.0001 kelvin). "The key to BOOMERANG's ability to obtain these images," explains Lange, "is the marriage of a powerful new detector technology developed at Caltech and the Jet Propulsion Lab with the superb microwave telescope and cryogenic systems developed in Italy." The two-ton telescope soared above 99 percent of Earth's atmosphere at an altitude of 37 kilometers on a NASA balloon that circumnavigated Antarctica in December 1998 and January 1999. BOOMERANG's $10^{1}/_{2}$-day flight ended within 50 kilometers of its launch site—not bad for an 8,000-kilometer throw!

(In a complementary effort, a Caltech team led by Professor of Astronomy Anthony Readhead is using a specially built radio telescope, the Cosmic Background Imager (CBI), to obtain CMB images at even sharper resolution. Together, BOOMERANG and CBI open an era of precision cosmological measurement that promises to provide new insights into fundamental physics.)

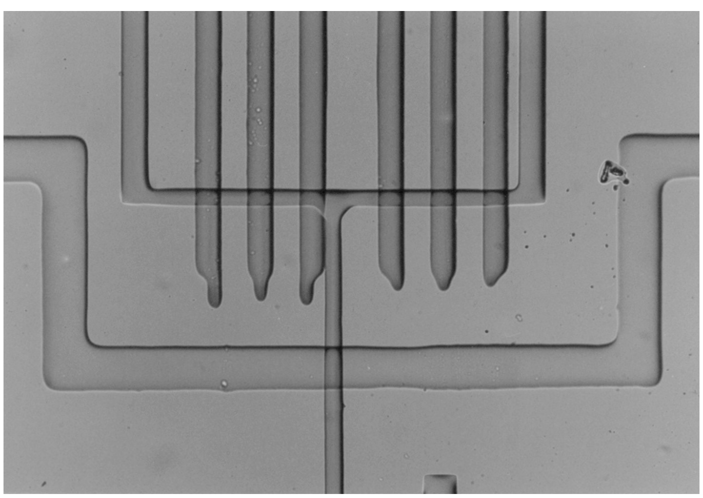
The first insight from BOOMERANG's data is that the universe is cosmologically flat, as explained at right. This agrees with a fundamental prediction of the "inflationary" model, a hitherto speculative, if widely accepted, scenario in which the universe violently and inexplicably grew from a subatomic volume to a respectable size just a split second after the Big Bang, stretching space flat in the process. So the flat-earthers have the last laugh: Columbus never sailed off the edge of the ocean, but Captain Picard may yet plunge off the edge of the universe. Except, of course, for the fact that the darn thing is infinite. □—*DS*



Left: BOOMERANG's button-sized heat-detecting elements, or bolometers, are freestanding spiderwebs micromachined out of silicon nitride and cooled to 0.3 kelvin—three-tenths of a degree above absolute zero. At that temperature, BOOMERANG can see the heat given off by a coffee maker on the moon, according to Jamie Bock. Bock, a research scientist at JPL and visiting associate in physics at Caltech, invented the detector technology and led the design and fabrication effort.



Above: The top panel shows a swath of BOOMERANG data 25 degrees wide. The bottom panels show the spot sizes predicted by different cosmologies. If space is an egglike closed curve (left), then parallel lines converge and the spots appear larger. If space is a saddle-shaped open curve (right), parallel lines diverge and the spots appear smaller. If space is flat (middle), the spots appear to be one degree in diameter.



This menorah-like object is actually a micromixer for fluids, cast from a single piece of soft rubber. The fluids flow from the top of the image to the bottom through the squared-off Y. The six "candles"—three on each arm—are the pressurizable channels that act as micropumps. The U-shaped channel across the stem of the candelabra is a pressurizable microvalve to control postmixing flow. The channels are about 50 microns wide.

Rubber Baby Micro Pumpers

Caltech researchers have developed an itty-bitty pump about five times the size of a red blood cell. Silicon micropumps have been made before, but this one is made of soft, flexible material and opens up an entirely new approach to building nanoscale devices, according to Associate Professor of Applied Physics Stephen Quake and his colleagues, who report their findings in the April 7 issue of *Science*. Unlike the silicon-based micromachining techniques derived from the computer chip-making industry, this technique, called multilayer soft lithography, creates intricate castings in soft rubber. The work is an extension of soft lithography casting, originally developed by George Whitesides (PhD '64) at Harvard University.

"Basically, it's plumbing on a very small scale," says Quake. "We are trying to show that for certain applications it is useful to make microdevices out of soft rubber, rather than the hard materials like glass or silicon used in traditional micromachining. In order to make a valve, one needs to figure out how to make it seal, which is usually done with

Freshman Clinton Conley (far right) had the pleasure of riding the Edison International–JPL Year 2000 Rose Parade float. Conley was a senior on the Fullerton, California, Troy High School Science Bowl team, which won the JPL-sponsored Southern California regional contest in 1999 and then went on to place seventh in the nation. In addition to a JPL sweatshirt, T-shirt, cap, and lapel pin and a "priceless experience," Conley said he obviously gained some name recognition, because that autumn, when JPL was looking for a Caltech student to ride the float, his name came up. Because of the parade's early start time for the benefit of the East Coast TV audience and the pre-parade judging, participants have to get up just about the time when most undergrads are getting to bed—but for a once-in-a-lifetime experience, it was well worth it. "I thought that the whole thing was overwhelming. I needed a lot of coffee to wake up," he says. □—ME

a rubber washer. We made the entire valve out of the sealing material."

The pump works because of the material's softness and pliability. Embedded in a clear rubber chip the size of a postage stamp, the pump is actually a series of tiny, multilayer channels that each measure 50 by 30 by 10 microns, or millionths of a meter. (By contrast, a red blood cell is about 7.5 microns in diameter.) The pump operates in a manner similar to the peristaltic motions by which food travels through the intestines. By applying pressure in one of the channels, another channel above it or below it in the 3-D matrix can be closed off, thereby allowing the channel to act either as a pump or as a valve.

While this research is mainly aimed at demonstrating the feasibility of the technique, Quake says the pump could have a number of practical applications, including drug delivery. Doctors could one day implant a biocompatible pump and reservoir system into a patient's body to deliver drugs for such things as allergies, pain, diabetes, and cancer. The device could allow the drug to be delivered in a time-released manner customized for the patient, and could also contain an analytical component that would enable regular monitoring of the patient's condition.

Quake's own lab intends to use the microfabricated valves and pumps in two devices: a DNA sizer, which is a replacement for the current DNA sorting technique known as gel electrophoresis; and a cell sorter, a machine that physically separates microscopic materials such as bacteria or viruses. Both devices originated from research in Quake's lab.

Caltech has licensed this technology to Mycometrix Corporation of South San Francisco, which will apply it to develop a variety of commercial products.

In addition to Quake, the others involved in the research are Axel Scherer, Professor of Electrical Engineering, Applied Physics, and Physics; Marc Unger (PhD '99), a postdoctoral scholar in applied physics; Hou-Pu Chou (MS '96), a graduate student in electrical engineering; and Todd Thorsen, a graduate student in biochemistry. □—*RT*

The family of planets (in order outward from the sun, starting at the top, plus Earth's moon and minus Pluto) has been imaged for this montage by a succession of spacecraft including Mariner 10, the Viking orbiters, Voyagers 1 and 2, and Magellan. The next step in getting to know our neighbors will be to sample their atmospheres, land on them, and eventually pick up some pieces. Prime targets are Mars and the moons of Jupiter and Saturn.

The Mariners, Pioneers, Voyagers, and Magellan gave us a global view of these diverse bodies. In the last five years, exploration has begun to shift from global to close-up views as we begin to sample these other worlds.

Sampling the Solar System

by Edward C. Stone

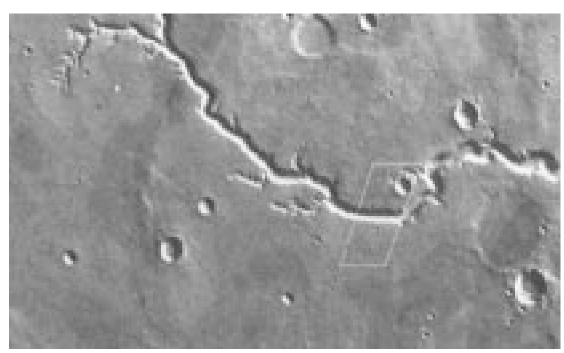
During the first four decades of the space age, missions of exploration have revolutionized our view of the solar system. The Mariners, Pioneers, Voyagers, and Magellan gave us a global view of these diverse bodies. In the last five years, exploration has begun to shift from global to close-up views as we begin to sample these other worlds —first in place, and then returning samples to Earth. The analysis of such samples is critical to our understanding of the geological, atmospheric, and climatological processes that have shaped our neighboring planets and their moons, and of what role those processes may have played in the origin of life.

The first samples returned to Earth were brought back from the moon in the late '60s and early '70s by the Apollo missions. The first missions to sample the surface of another planet were the two Viking landers that touched down on the surface of Mars in 1976 to search for both extant and extinct life. They didn't find any. Because of high levels of ultraviolet radiation and a lack of protective ozone, the surface of Mars is quite sterile, and a highly oxidizing material in the soil destroys any organic substances, including those deposited by meteorite impacts.

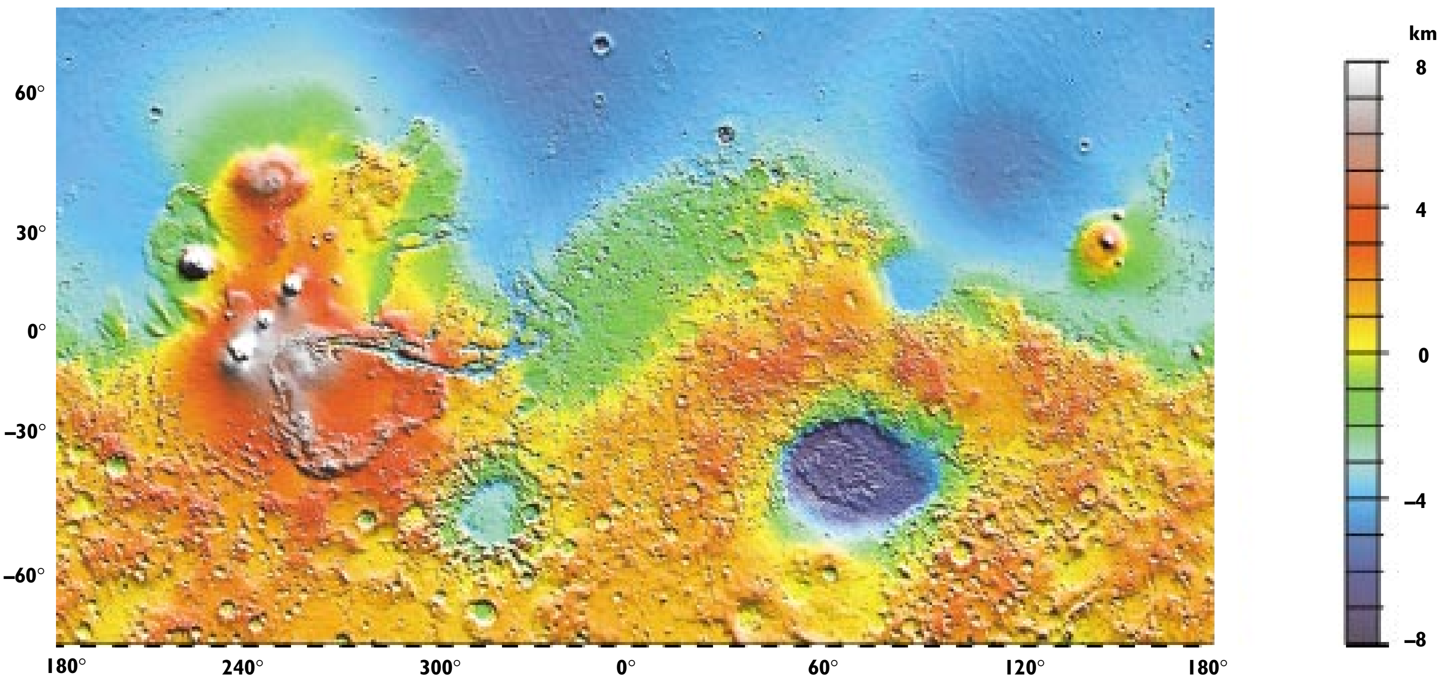
The Viking missions asked specific questions: Is there life? Was there life? The disappointing answer was clearly no. But, at about the same time, our view of life on Earth was beginning to change. The underlying assumption was that the sun was the source of energy for life and that photosynthesis was at the bottom of the food chain. But in 1977, one year after Viking landed on Mars, oceanographers exploring boiling water vents on the floor of the Pacific discovered that life was thriving on the chemical energy coming from inside the Earth.

In Antarctica there are algae that are quite viable at near-freezing temperatures. Drill one or two miles into the Earth's crust, bring up the rock, and if there's water in the rock, there's life. (see *E&S*, 1999, No. 1-2, "The Search for Extraterrestrial Life," by Kenneth Nealson.) The Rio Tinto in Spain has a pH of 2, a very acidic river, yet there's life there too. It turns out that where there is water here on Earth, there is life—microbial life. This has renewed interest in exploring the possibility of life elsewhere by asking not whether there is life or was life, but rather: Where was the water, and perhaps where *is* the water? Understanding the geological, atmospheric, and climatological processes that control the presence or absence of water on other bodies in the solar system will help us discover the answer.

Mars is again a focus of our search. The planet is similar to Earth in that there is water in the atmosphere in the form of clouds and haze, but there is no liquid water on the surface. Billions of years ago, however, there was a lot of water, and massive floods carved huge canyons. What might the water cycle have been like when there was liquid water on the surface of Mars? The Viking image below of one of these canyons illustrates an interesting aspect of the puzzle. There are no tributaries. On Earth, creeks flow into streams that flow into ever-larger rivers in massive water-



Viking Orbiter I showed massive dry riverbeds on Mars, where water must have flowed billions of years ago. But there are no tributaries. Where did the water come from?



collection systems. On Mars there seems to be no similar water-collection system. Mars Global Surveyor, orbiting since 1997 (Michael C. Malin, PhD '76, is the principal investigator for the Mars Orbiter Camera, and Arden Albee, professor of geology and planetary science, is the project scientist), has provided a high-resolution picture of this area (left) and clues as to what might have happened. It appears as though the water burst out of the canyon walls from underground, creating massive floods carrying rock and debris downstream into the basin. Presumably the water erupted where there was sufficient heat from volcanic activity to have kept it liquid, rather than frozen, beneath the surface.

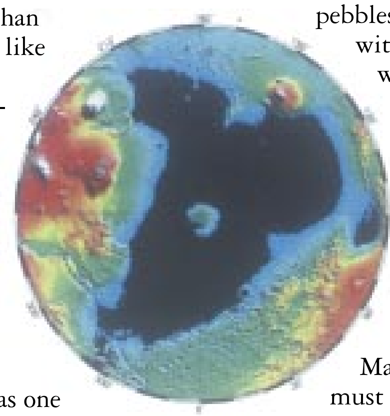
Mars Global Surveyor captured this higher-resolution image of a stretch of Nirgal Vallis shown on the previous page (outlined by the white box). The little side canyons jutting out of the main canyon wall on the upper side indicate an underground source of the flood waters that created it. (Malin Space Science Systems)

To understand this different water cycle, we must look at where there might have been ocean basins on Mars. The laser altimeter on Mars Global Surveyor measures the height of the surface of Mars very accurately. The topographic map above illustrates the great asymmetry between the southern hemisphere of Mars, which is several miles higher than the average, and the northern hemisphere, which is several miles lower than average. (The relief on Mars is something like 20 miles from highest to lowest point.) There are ancient streambeds in the southern hemisphere, carved by water that one time flowed northward into this great low-lying basin.

Several years ago Timothy J. Parker at JPL inferred from Viking data that an ancient shoreline might exist around this northern plain. He and his colleagues identified two possible shorelines. Their analysis was based on the observation that inside the inner contour it's very smooth, as one might expect for the bottom of an ancient ocean. Between the first and second contours, it's somewhat rougher, and above the second contour the terrain rougher still.

With Mars Global Surveyor's accurate height measurements, we can conjecture what that ocean might have looked like if the basin had been filled to a depth of about 5,000 feet (see below). There is debate, however, about whether there ever was a standing ocean in this region. In the few spots along this potential shoreline examined in high-resolution Global Surveyor images, there's no evidence of a shoreline. Perhaps the water flowed in and immediately froze, forming a layer of permafrost.

On July 4, 1997, Mars Pathfinder landed near the mouth of one of the massive canyon systems flowing into this basin. Matthew Golombek, the Pathfinder project scientist, and his team purposely picked a spot far enough downstream from the mouth of the canyon so that the slowing flow could have carried only smaller rocks to the site. Sojourner examined conglomerate rocks, dust, pebbles, and sand, all consistent with a Mars that was once warm and wet, since flowing water tumbles material to make pebbles, sand, and dust. The dust itself proved to be magnetic, an indication that iron may have been leached out of the crust.



How long ago might water have flowed on Mars? To answer that, we must ask first when the atmo-

Left: Mars Global Surveyor's laser altimeter yielded this precise global relief map of Mars in Mercator projection. The red areas are about four kilometers above the average surface height, and the blue of the northern hemisphere, about four kilometers below. Note the great difference between the northern and southern hemispheres. Seen in a pole-to-equator view (below, left), the northern hemisphere topography suggests where an ocean might have been. The laser altimeter uses its own coordinate system, in which longitude increases as you go eastward—the opposite of the standard system. (Head et al.)

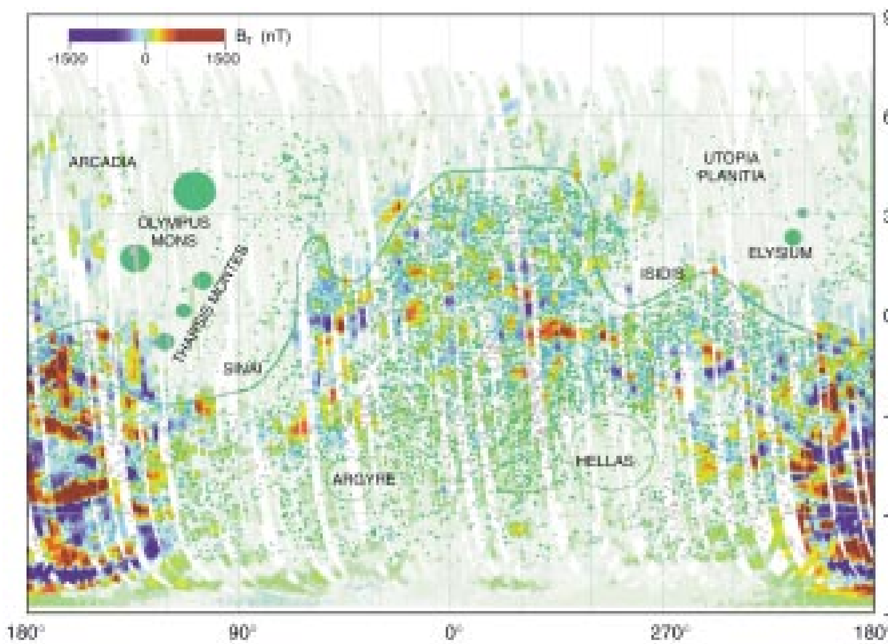
sphere became so thin that water could not exist in liquid form. (Today it's less than one percent of the pressure on Earth; under such low pressure, liquid water will vaporize.) Various processes contribute to atmospheric loss, including weathering, erosion by meteoritic impact, and sputtering from ions in the solar wind colliding with the upper atmosphere. A global magnetic field will shield the atmosphere from sputtering by deflecting the ions away from the planet.

Earth has a global magnetic field like a bar magnet, with a north pole and a south pole, but Mars does not. Instead, the magnetic field exists only in local regions on the surface, in a bar code pattern of alternating north and south polarities. (The magnetic field is positive if it's red, negative if it's blue in the illustration below.)

This surprising finding means that the magnetic field is "frozen" into the rock. In other words, there was a global magnetic field at the time the rock cooled, and the rock preserved the direction of the magnetic field at the time it cooled. This is observed on Earth where seafloor spreading at the bottom of the oceans is fed by magma oozing from the interior. Earth's magnetic polarity regularly reverses, so that as new seafloor cools, it freezes in the direction of the magnetic field at that epoch, creating an orderly magnetic pattern.

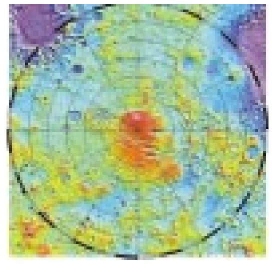
Given such a model, the locations of the frozen remnant magnetic fields are quite striking. Notice that there's no remnant magnetic field in the north, where the surface is younger than 3.9 billion years, as indicated by the relative paucity of impact craters. The southern hemisphere, however, is heavily cratered, indicating that its surface dates from the period of heavy bombardment that ended 3.9 billion years ago. There are remnant magnetic fields in the older part of Mars, but not everywhere; there's none, for example, where there are very large impact basins (one of these, Hellas, is six miles deep). A major impact would have heated and demagnetized whatever was there. Had there still been a global magnetic field as the impacted material cooled, it would have been remagnetized. Since that did not happen, the impact must have occurred at a time when there was no longer a planetary magnetic field. This tells us that there was a global magnetic field on Mars for only the first few hundred million years, before the heavy bombardment stopped. By then, the planet's churning interior, which creates the field, had evidently cooled enough that the churning stopped and the magnetic field decayed away.

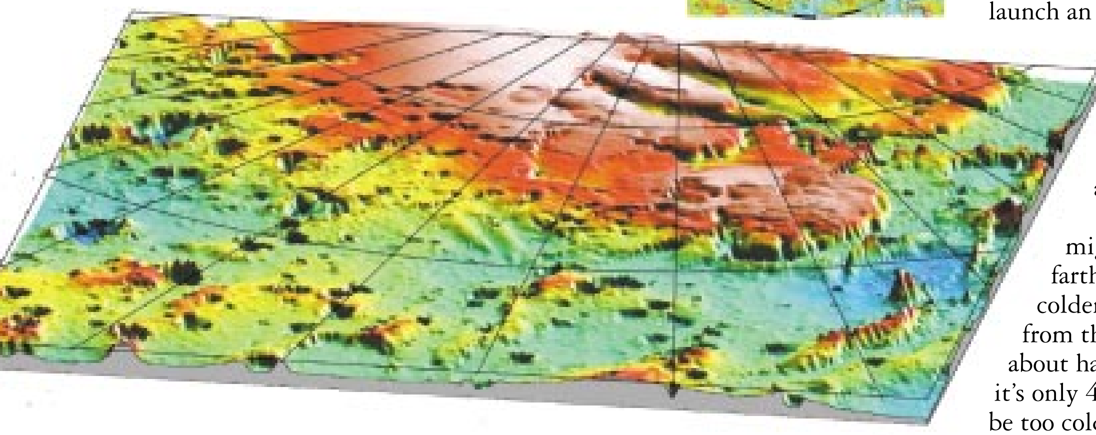
Below: Mars's spotty bands of magnetic field (red is positive, blue is negative) are located only in the older, heavily cratered southern hemisphere, indicating that, when the impacts stopped after the first 500 million years or so, there was no magnetic field left—only these remnants "frozen" into the rock. Without a magnetic field, the solar wind would have swept away the atmosphere. Hellas and Argyre are two deep impact craters, also visible in the relief map on the opposite page. (Acuña et al.)



Without a planetary magnetic field to shield the atmosphere, the million-miles-per-hour ionized wind from the sun can sweep in and carry away the atmosphere, little by little, year by year. This is what likely happened on Mars, until today there's very little atmosphere left, making liquid water on the surface of Mars no longer possible.

There is still some water on Mars besides that in the atmosphere—frozen in the polar caps. The north polar cap is composed of both water ice and dry ice (solid carbon dioxide), forming a very intricate pattern. In the winter dry ice covers most of the surface, but as it sublimes into carbon dioxide gas during the summer, what is left is





Top: The south pole of Mars, seen here by the Mars Global Surveyor's laser altimeter, rises to a height of 4,000–5,000 meters (red). The small polar cap, made of dry ice, sits atop a terrain that scientists think may be water ice, dry ice, and dust built up over billions of years. The layers of this terrain, where the ill-fated Mars Polar Lander was aimed to search for water, can be seen in the edge-on view at bottom.

mainly water ice. In order to determine how much water ice is there, we need to know how thick it is, and Mars Global Surveyor, with its laser altimeter, has been able to tell us that. The typical thickness is about 3,300 feet, and peak thickness is about 10,000 feet. So we now know how much water is on Mars in the north polar cap: about half as much as is on Greenland or about a tenth as much water as we believe must have been on Mars to create the massive canyons.

The visible south polar cap is smaller, and it's all dry ice. But if we measure the topography, we find that there's a much larger accumulation of material there than just the small white polar cap. The polar cap is sitting on top of a large deposit called the "layered terrain." We believe that this might be a buildup of water ice, dry ice, and dust, accumulated over billions of years. This south polar region is where, last December, we were trying to land the Mars Polar Lander to search for water. We were aiming for a spot at a height of about 3,000 feet above the surrounding plain, believing that we might be landing on an ancient icy polar cap. Unfortunately, the landing was not successful, and no data were returned from the surface.

But we have an opportunity to go to Mars every 26 months, when Earth and Mars are positioned in their orbits so that a spacecraft can "hop" from one to the other. The next opportunity will be in March and April of 2001, and we're currently looking at exactly what the sequence of missions should be. We want to sample the surface of Mars in interesting places, perhaps where there once may have been thermal activity similar to Yellowstone National Park. We can identify such locations by using orbiting spacecraft with different sets of instruments to help determine where it may have been wet at one time. Landers with instruments that allow us to measure and to sample in situ will eventually lead, perhaps by the end of this decade, to landers with rovers to acquire samples for launch into Mars orbit and return to Earth. In addition to the NASA program, the European Space Agency is planning to launch an orbiting mission called Mars Express, to arrive in 2003. It will have a radar system, which JPL will provide, to look for water underground. The Japanese spacecraft Nozomi will also arrive in late 2003 to study the Martian atmosphere.

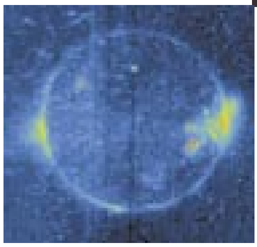
Mars is not the only place where we might look for water. Jupiter is five times farther from the sun than Earth, and much colder than Mars (which is $1^1/_2$ times as far from the sun as Earth). At Mars, the sun is about half as bright as we see it, but at Jupiter, it's only 4 percent as bright, so it would seem to be too cold for there to be an ocean.

Jupiter is a giant gaseous planet with no solid surface, but it has several interesting moons, in particular Io and Europa. Although they're distinctly different from each other today, they were probably much alike $4^1/_2$ billion years ago. But they don't look the same today because of great differences in geological activity. When Voyager flew by in 1979, it found Io to be the most volcanically active body in the solar system. The Galileo spacecraft returned to Jupiter in December 1995 and has been orbiting the planet since then. Every couple of months it can fly close by a moon and provide hundred-times-better images than Voyager could.

Io is just a small moon, but it has eight active volcanoes and more than a hundred hot spots—active volcanic areas glowing with lava flows, a hundred times more than here on Earth. How can such a small moon so far from the sun be so active? The answer is tidal heating. We're familiar with the tides that cause our ocean surfaces to bob up and down about every 12 hours as Earth rotates under the moon. Jupiter is so massive that its moons, as they orbit Jupiter, have a tide in their crust. We estimate, as Io orbits Jupiter every 1.8 days, that its crust is flexed up and down by about 100 feet. This tidal flexing produces enough energy to drive the remarkable volcanic activity on Io.

Io is six Jupiter-radii away from the planet's center. Europa is 10, so the same flexing occurs on Europa, but not as strongly. In 1979 Voyager found what looked like streaks drawn on Europa's surface. From spectroscopy, we know Europa is covered with water ice. Since the surface of Europa is the smoothest in the solar system, with no mountains or valleys, the idea soon emerged that perhaps it is a layer of ice on a liquid-water ocean. The same tidal heating that drives the

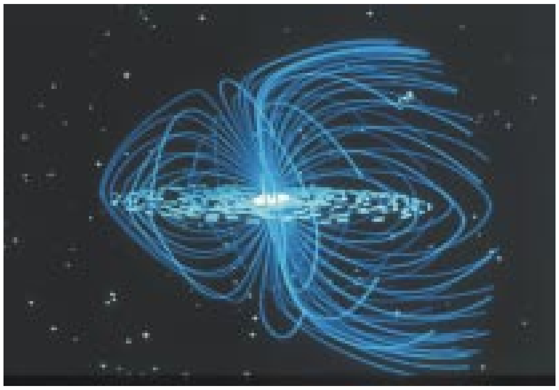
Right: Two of Jupiter's moons, Io (left) and Europa, caught here by Voyager 1 in 1979, might harbor conditions conducive to life. Io, shown below by Galileo in the eclipse of Jupiter's shadow, bristles with volcanic activity. Hotspots, increasing in brightness from yellow to red, indicate the volcanoes and their oceans of lava.



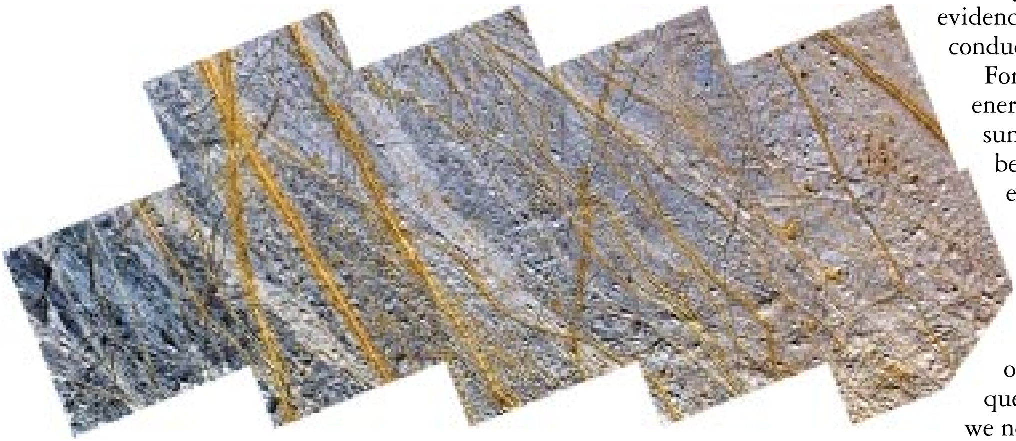
volcanoes on Io melts the ice beneath Europa's icy crust.

Voyager flew within 130,000 miles of Europa. Galileo, in orbit around Jupiter, can fly by at a distance of only a few hundred miles once every several months. These close-up views have revealed cracks and ridges and places where the surface has been broken, as if from a warm upwelling of a substance with the reddish-brown color characteristic of magnesium sulfate—Epsom salts—an indication of salty material seeping from below. The cover image on this magazine suggests a highly patterned, regular surface, but with pieces that have broken apart, as ice floes do in spring in the Arctic, and floated away before the material in between refroze.

Mobility on the surface suggests some sort of fluid beneath. But how long ago did this happen? Is it possible that it's still going on? Is there evidence that suggests that there might be liquid below the surface and not just soft ice? Again, the magnetic field is giving us a clear answer to these questions. Jupiter has an immense magnetic field, generated inside the planet just like Earth's. And like Earth's, Jupiter's magnetic field is not lined up with the rotation axis but is tilted a bit, so that the magnetic field wobbles as Jupiter rotates. Dave Stevenson, the Van Osdol Professor of Planetary Science, has suggested that as this wobbling magnetic field sweeps past Europa, its changing directions will generate a magnetic field in Europa, provided there is an electrical conductor beneath its surface (a salty ocean will do nicely). Since the Jovian magnetic field at Europa wobbles from one direction to the other every $5^1/_2$ hours, the induced Europan magnetic field should also reverse direction with the same period. This is exactly what Galileo measured—very strong evidence that beneath the icy crust there's a conducting liquid, most likely a salty ocean.



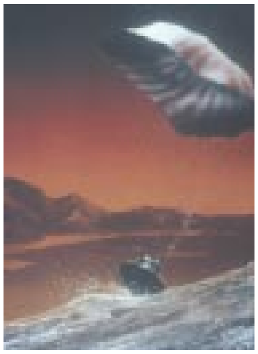
Right: Jupiter's tilted, wobbling magnetic field generates a continually reversing magnetic field in Europa—exactly what was predicted if an electrical conductor, a salty ocean, say, were hidden under its crust.



Below: The cracks and ridges seen by Galileo in Europa's icy crust also suggest that it's being flexed as it orbits Jupiter. (U. of Arizona/DLR)

For life, though, you also need a source of energy. On Europa it certainly can't be sunlight. Perhaps there are volcanic vents beneath the ocean. Perhaps the radiation environment of Jupiter creates a complex set of organic and oxidizing materials on Europa's surface that are cycled back into the ocean in upwellings between the cracks; that might be a source of energy on which microorganisms could exist. To answer the question of whether there's energy, and life, we need to sample both the surface and—if

Below: An artist's rendering of the Huygens probe, carried by the Cassini spacecraft, landing on Saturn's moon Titan, which it is scheduled to do in 2004; the top arrow in the bottom image indicates the landing site. This image was made of Titan's surface (here in Mercator projection) by the Hubble Space Telescope's Wide-Field and Planetary Camera 2, which was able to peer in the infrared through Titan's thick, orange haze for the first time. Scientists believe that the dark areas may be hydrocarbon lakes and the bright ones higher terrains. The lower arrow points to what may be a continent-type feature the size of Australia.



we can find a place where it's thin, broken up, or cracked—below the surface.

The next step is to send an orbiting spacecraft to Europa, so that we can map the entire surface rather than just the few small areas that we have from Galileo. We're currently developing a technology that will allow us to return to Europa in the next 10 years, placing a spacecraft into orbit at a distance of about 125 miles above its surface. We can then use a laser altimeter to measure exactly how much that surface is flexing. If it flexes 100 feet, we'll know it's a very thin crust; if it flexes only three feet, it's frozen solid—although that would be unlikely, given the magnetic field data that we already have. Perhaps a radar system could measure the thin spots in the ice, and a high-resolution imaging system should reveal the most promising spots for a future mission to land and sample the surface on this world.

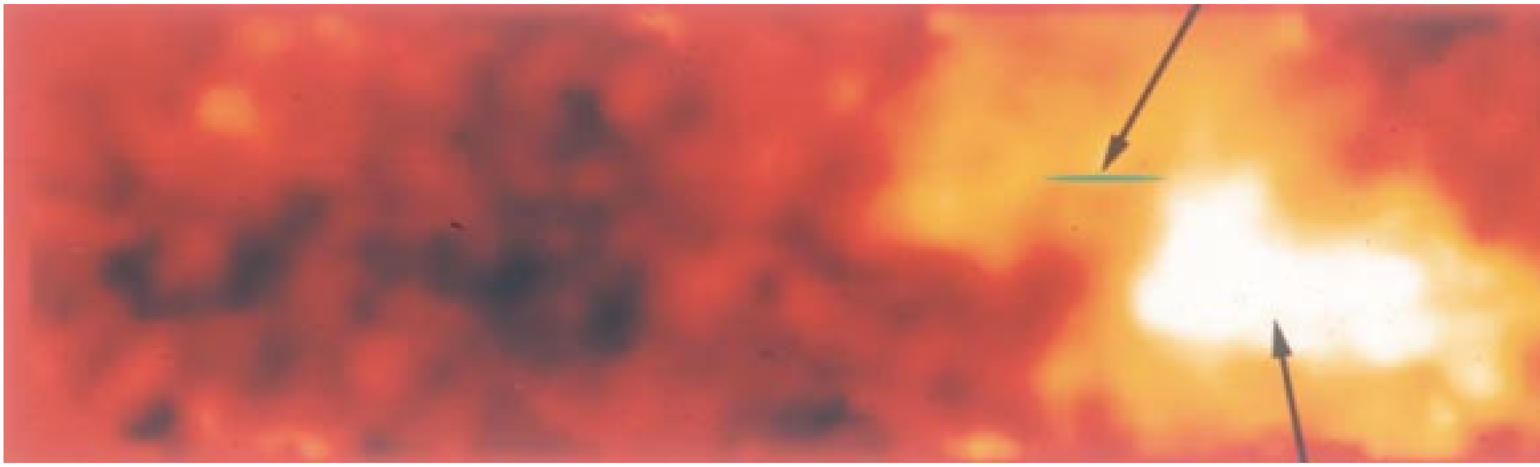
Today, there are no other places in the solar system where we think there may be liquid water. But there are other places that may help us understand the chemical circumstances associated with the origin of life. One of these is Saturn, 10 times as far from the sun as Earth, with only 1 percent of the sunlight. Saturn is a giant planet, like Jupiter, and one of its moons, Titan, is about the size of the planet Mercury. Unlike Mercury, however, Titan has a very dense atmosphere, with a surface pressure about 60 percent greater than on Earth. The atmosphere is mainly nitrogen, like Earth's, but there's no oxygen, which on Earth was produced by microbial life. Titan does, however, have a trace of methane (natural gas, CH_4), and solar and particle radiation converts that methane into complex organic molecules. Some of the molecules become polymerized, forming particles large enough to block visible light and obscure Titan's surface: it looks fuzzy because of all the organic haze in its atmosphere. The organic chemistry that's occurring today in Titan's atmosphere may in some important ways resemble the chemistry that occurred in the early Earth's atmosphere before life evolved.

Fortunately, the Hubble Space Telescope can peer through Titan's haze. Using the infrared rather than visible light, Hubble can image Titan's surface and discriminate between lighter and darker regions. Jonathan Lunine (PhD '85), Professor of Planetary Science Yuk Yung, and Dave Stevenson calculated that some of the organic material created in that atmosphere should be liquid, resulting in rain and lakes of liquid hydrocarbon. Those lakes would be very dark, so perhaps these darker spots are the low regions and the brighter ones are higher.

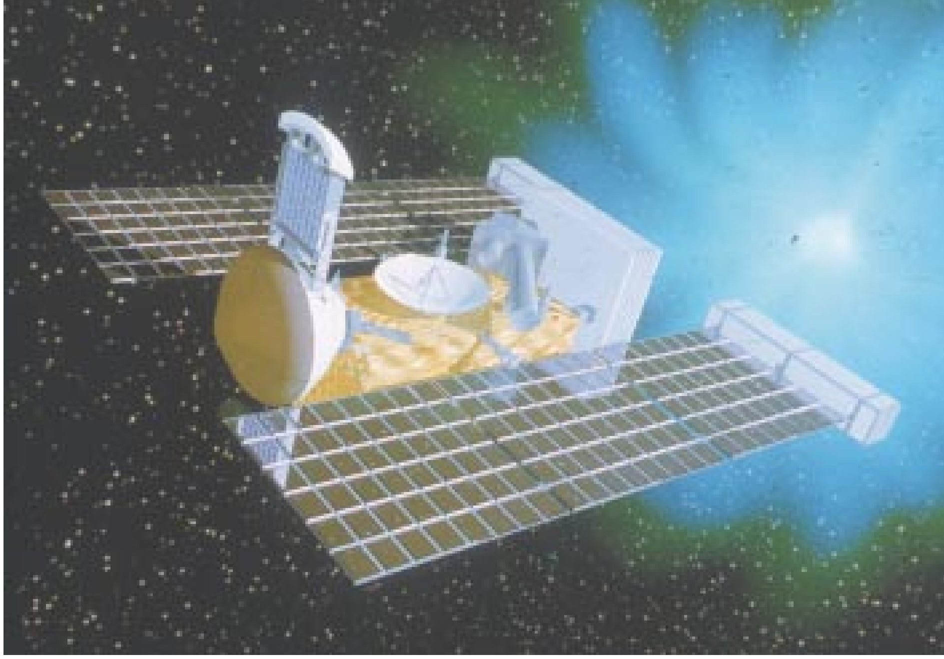
In December 2004, we will sample Titan's atmospheric chemistry and map the surface. Cassini, launched in 1997, will begin orbiting Saturn in July 2004, carrying an imaging radar system, built jointly with Italy, that will map the surface through the haze. Cassini also carries the Huygens probe, built by the European Space Agency, which will plunge into Titan's atmosphere with instruments specially designed to analyze the organic molecules present. A camera will return images of the surface during descent. We have no idea whether Huygens will splash down into a liquid or crash onto a solid surface—that's part of the process of discovery. Eventually we may want to return to Titan to sample the surface with experiments designed to identify the materials that have been deposited there over the last millions of years, a frozen record that might tell us about the chemistry that occurred on Earth before life evolved.

Still more clues about the early solar system might come from comets, the ice and rock left over from when the solar system formed. Many comets ended up inside Jupiter, Saturn, Uranus, and Neptune, but these giant planets also scattered many comets out into the Oort cloud that surrounds the solar system. Occasionally, a comet is nudged into a journey back near the sun, where the heat causes the ices to sublime, creating a beautiful tail. Twenty years ago, it was expected that comets, composed of water ice, would have bright surfaces, but we now know they're covered with a charcoal-black material.

When the European Giotto spacecraft flew



Far right: The Stardust mission will visit comet Wild 2 in 2004 and return to Earth with bits of comet dust captured in the apparatus projecting above the conical return capsule. Embedded in that holder, shown at lower right, is an airy silica substance called aerogel. When the particles encounter the aerogel at 14,000 miles per hour (right), they slow down and are trapped.



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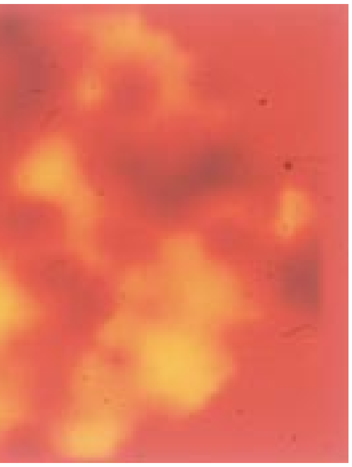
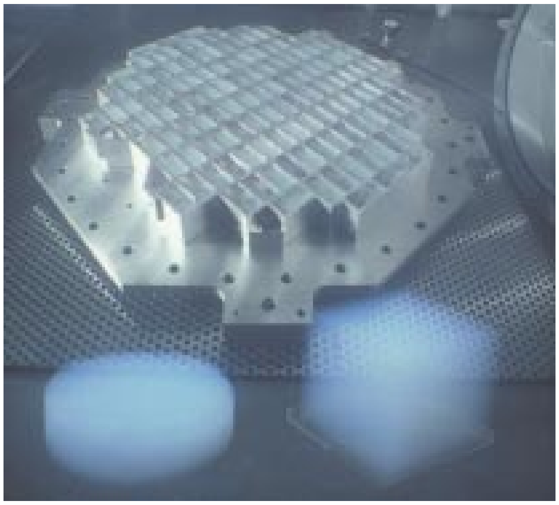


through the coma of Halley's comet in 1986, it found that the material coming off the comet contained atoms of carbon, hydrogen, oxygen, and nitrogen—the atoms basic to organic molecules. The fact that it's black certainly suggests carbon-bearing material. What is this material? Where did it come from? And what role might it have played in the origin of life here on Earth and possibly elsewhere in the solar system? All the planets, as they were forming, were bombarded by these comets and their black material. We can't answer any of these questions until we know what that material is. We need a sample.

We have two approaches under way. Deep Impact, which will be launched in January 2004, will fire a 1,000-pound copper projectile into comet Tempel 1 as it flies by. The resulting crater, about 70 feet deep and 300 feet across, will allow us to look below the surface. At the same time, material splashed out by the blast will be analyzed by spacecraft instruments during flyby. All these fireworks will help celebrate July 4, 2005.

We also want to bring a comet sample back, a task assigned to the Stardust mission. The challenge is to collect the comet dust as we fly through the coma at 14,000 miles an hour. If we use a sheet of ordinary material to collect the comet dust particles, they will crash into it at 14,000 miles an hour and evaporate. So Peter Tsou at JPL developed aerogel, a substance made of silica that's mostly nothing. The best analogy is cotton candy—sugar spun up so there's not much there. Aerogel's silica blocks are about six times the density of air, but rigid enough to be embedded in a holder. Stardust, with its aerogel blocks extended, will fly by comet Wild 2 in January 2004 and return the sample to Earth in January 2006, landing in Utah. We will have thousands, if not millions, of tiny bits of comet dust that can be analyzed for the first time.

Just as the first decades of planetary exploration revolutionized our view of the solar system, there



is every reason to believe that sampling the solar system in the decades ahead will greatly expand our understanding of the diverse worlds around us and of the conditions essential to the origin and evolution of life, not just here on Earth, but elsewhere. □

Ed Stone has been director of Caltech's Jet Propulsion Laboratory since 1991, but his connection to space goes back to his first cosmic-ray experiments on Discoverer satellites in 1961. Since then, he has been principal investigator on nine NASA spacecraft missions and co-investigator on five more, as well as project scientist for the spectacular Voyager missions. Stone, who came to Caltech as a research fellow in 1964 after earning his PhD from the University of Chicago, was named professor of physics in 1976 and served as chair of the Division of Physics, Mathematics and Astronomy from 1983 to 1988. He is now a vice president of the Institute and the Morrisroe Professor of Physics. This article was adapted from Stone's February Watson lecture; his series of Watson lectures on Voyager's planetary flybys appeared in E&S *from 1979 through 1990.*

The sixth annual Caltech Biology Forum, held on February 24, was devoted to the burgeoning field of stem-cell research, which Science *magazine hailed last December as 1999's Breakthrough of the Year. This article is adapted from the remarks of three of the forum's speakers, who were joined by David Anderson, professor of biology and investigator, Howard Hughes Medical Institute, and by moderator Robert Lee Hotz, science writer for the* Los Angeles Times. *The event was cosponsored by Huntington Memorial Hospital, with which several Caltech faculty collaborate; and the San Gabriel Valley Newspaper Group, publishers of the* Pasadena Star-News.

The kicker is figuring out how to steer the cells down one of those long, winding developmental pathways...to get what you want.

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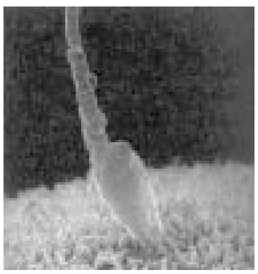
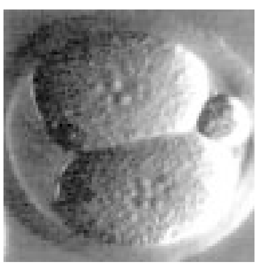
Barbara Wold

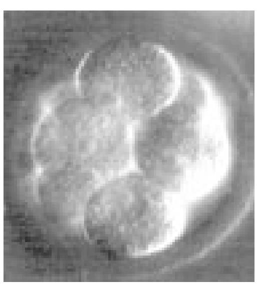
Professor of Biology Barbara Wold earned her PhD in biology from Caltech in 1978, and has been a faculty member since 1981. Her research focuses on the elaborate regulatory machinery that guides the development of muscle cells. She is also the director of the L. K. Whittier Gene Expression Center, established on campus in 1999, which draws scientists from several disciplines to the task of finding out what the roughly 100,000 genes in the human body do.

Left: This gallery of false-color scanning electron microscope pictures hints at the diversity of cell types obtainable from one totipotent stem cell. Clockwise, from upper left: a thicket of nerve cells and an astrocyte (green), which is also part of the nervous system; the epithelial cells that line the air sacs in your lungs; a smooth (involuntary) muscle cell; red blood cells, a T lymphocyte (green), which is a kind of white blood cell, and platelets (blue), which help the blood clot.

Stem Cells: The Science of Regeneration





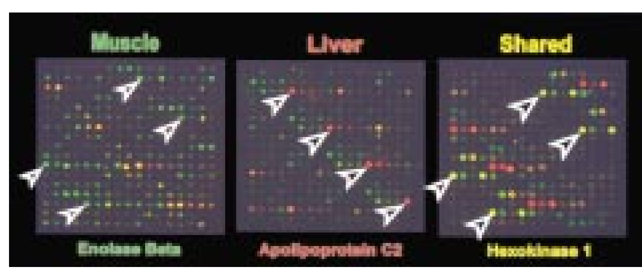


Above: A successful sperm sets off a rapid series of cell divisions in the fertilized egg, shown at two, eight, and approximately 40 cells.

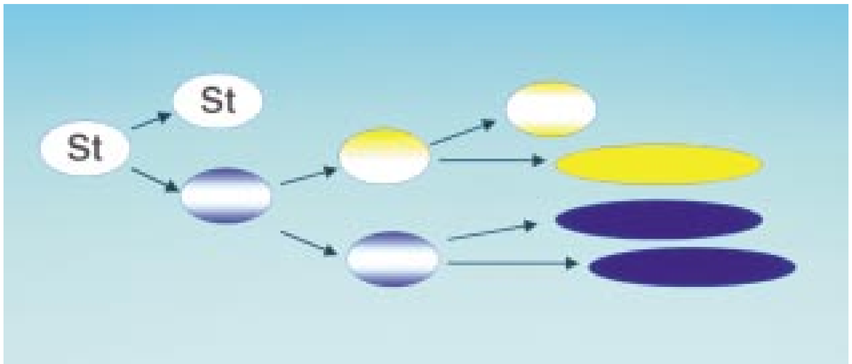
It's hard to be a developmental biologist and not be fascinated by stem cells, which are "primitive" cells that give rise to other, more specialized, cell types. The story of stem cells is really two tales—one is the development of the embryo, and the other is regeneration in adults in response to injuries, degenerative diseases, and normal wear and tear. Many of our tissues—bone, the hematipoetic blood cell system, muscle—have to keep rebuilding themselves all the time just to keep us at steady state. Development begins when a sperm fertilizes an egg, and the cell begins to divide. You ultimately end up with many diverse cell types, even within one tissue. This raises an issue that will come up again and again—there is a big difference between replacing cells of a given type as a form of therapy, versus building a whole organ, like a kidney or a heart. The former we can begin to think about. The latter is way out there, and I think there's been some confusion in the popular press about this.

Cells come to be different through a series of stepwise changes in the pattern of genes that the cells express, or "turn on." The pattern can change in response to external signals, either from other cells—growth factors and hormones—or environmental cues. Or the changes may be programmed in the genes' DNA. So each time a stem cell divides (and sometimes even without dividing), internal and external signals cause it to choose from a progressively smaller number of paths. And at the very end of the trail are the so-called differentiated cells—red blood cells and white blood cells, the neurons in your retina, et cetera.

Differentiated cells have various shapes and functions because they express vastly different sets of genes. Each of your cells has a complete set of all the genes needed to make you—roughly 100,000 genes in all. Of those, maybe 5,000 are needed for the basic business of simply being a cell. In addition, each cell expresses maybe 2,000 to 4,000 genes that make that cell different from other cell types. We can now measure gene expression en mass, as shown below, in which a muscle cell is compared with a liver cell. The green dots on this microscopic chip represent genes expressed only in muscle, and the red dots, ones only expressed in the liver. Things common to both cell types come out yellow or yellow-orange. So we can look at vast numbers of genes



The arrows point to four copies each of enolase beta, a gene known to be specifc to muscle tissue; an apolipoprotein gene, similarly specific to liver; and a gene common to both cell types. Having this experiment correctly light up the genes we know gives us confidence that the genes we don't know are behaving the same way.



Stem cells remain like their parents or change into other cell types in response to internal and external cues. Here we have a totipotent stem cell ("St") leading to a pluripotent one (half blue) leading to a unipotent one (half yellow). The other blue pluripotent cell undergoes a gene-expression change without dividing, producing two differentiated cells in its next division cycle.

and figure out which ones are particular to each cell type and which ones are shared.

Now, stem cells aren't really any single kind of cell, but are cells that exhibit the quality of "stemness." "Stemness" is really a dual capacity—these cells can, at once, produce more progenitor cells just like themselves, and also produce other progeny that go on to assume the distinctive forms and functions of differentiated cells. This is usually done when a stem "mother cell" divides to produce two different daughter cells: One daughter retains the same properties as the mother cell, and the other goes on to acquire new properties.

There are three major classes of stem cells, based on what they have the potential to become. The earliest cells, from the fertilized egg through the first few division cycles, are totipotent—able to become any kind of cell under the right circumstances. You can grow them in a dish, and they will divide infinitely and retain this totipotent quality. Next come the pluripotent, or multipotent, cells, which can become more than one kind of cell but no longer contain the potential to become all cell types. And finally there are unipotent cell types, such as the muscle-cell progenitors that my lab works with. These still have the quality of regenerating, but have pretty well decided that they're going to become muscle. (Actually, our lab recently discovered that our muscle cells also have the potential to become fat cells, which is kind of scary when you think about it. I guess, deep down, we all knew this already.)

Since totipotent cells can become any kind of cell, it suggests a strategy for cell therapy—replacing cells in your body that have died or don't work properly as a consequence of some disease like muscular dystrophy, which is my field. Adding back stem cells has also been a very large part of the thinking about treating Parkinson's, and correcting certain diseases of the blood. The kicker is figuring out how to steer the cells down one of those long, winding developmental pathways through the many decisions to get what you want. Much depends on the cell type that you're trying to generate. And you may want to stop differentiation at a certain point and have the process finish once the cells are in the patient. But we have some pretty serious distance to go before we can do everything in reality that we can do conceptually.

I'd like to emphasize a distinction that I made earlier in passing—building an organ is a whole lot more complex than providing just one cell component, however important, of that organ. Growing blood or muscle progenitors is possible—it's done all the time with mice. Differentiating them is possible—we know enough about the right environments, in some cases, to nudge them in the right direction. But that's way different from growing a kidney or a heart. We're not even vaguely close to that. It would be very exciting, and I hope we'll eventually learn to do it, but it's pretty much in the science-fiction movieland realm right now.

One sometimes hears stem cells mentioned in conjunction with Dolly, the cloned sheep, and here's why: You could take the nucleus from one of your adult cells, as was done with an adult sheep, and fuse it with what's called an enucleated egg—one from which the nucleus, which contains the genetic material, has been removed—and implant it in a foster mother. Then you could make custom embryonic stem cells of your own personal genetic type for your own personal therapy. This would bypass the problem of tissue rejection, and the issue of where to find donors. Or, of course, you could essentially generate your own newborn identical twin, which is what Dolly

Why would you want to create an identical twin that's 20, 30, 40, 50 years younger than you?...I have yet to hear a persuasive argument for why cloning humans is a good thing to do, and it seems to me that most of the reasons for doing it are bizarre.

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is to the adult sheep from which the cell was taken. All the scientists I know consider doing this latter in humans to be totally unacceptable ethically.

Why would you want to create an identical twin that's 20, 30, 40, 50 years younger than you? The notion that this individual would be like you, in the sense of having had your experiences and sharing your thoughts, is clearly not the case. And think about the burden of expectation on, say, a clone of Einstein. What kind of life would that person have? There's also the issue of whether the clone would be healthy over a human life span, which is seriously in doubt. As the cells in our body age, they undergo changes to their DNA. For example, the telomeres—the ends of the chromosomes—get shorter, which appears to act as some sort of clock that may tell the cells when to die. Some of this is apparently reversible, or you wouldn't get all the way to Dolly. Nevertheless, it's not clear what the long-term prospects are. Furthermore, many of the cells in our adult bodies contain mutations that the fertilized egg didn't have. As we age, our DNA gets damaged by environmental factors, such as ultraviolet light, and errors can creep into the DNA when it replicates during cell division. Normally, this doesn't matter much—if a heart gene is mutated in a skin cell, who cares? It doesn't need that gene anyway. But when you make an entire human being from that cell, that person is at risk. Similarly, as we age, our cells individually accrue mutations of all sorts, including ones that lead in the direction of cancer without yet being frankly cancerous. Thus a cell can appear quite normal, and therefore be selected as a donor, but in fact vastly raise the likelihood that the cloned individual will develop cancer, and develop it at an early age. And if the clone has kids, the mutations will be passed on as part of their genetic patrimony, so we can really pollute the gene pool quite rapidly by introducing all sorts of genetic diseases. I have yet to hear a persuasive argument for why cloning humans is a good thing to do, and it seems to me that most of the reasons for doing it are bizarre. Most people are repulsed by the idea; I am one.

In conclusion, using embryonic stem cells for replacement therapy has some virtues and some liabilities. It solves the tissue-rejection problem. It guarantees donor availability. It offers the prospect of replacement of many different kinds of cells. On the other hand, there's the problem of providing the right signals—we know them for a few tissues but not for many. Every patient presents a different environment. And there's concern about unwanted genetic changes that might have occurred in your donor nucleus.

[Regeneration] is really very widespread among animals, and for reasons that are not understood, mammals have largely lost it.

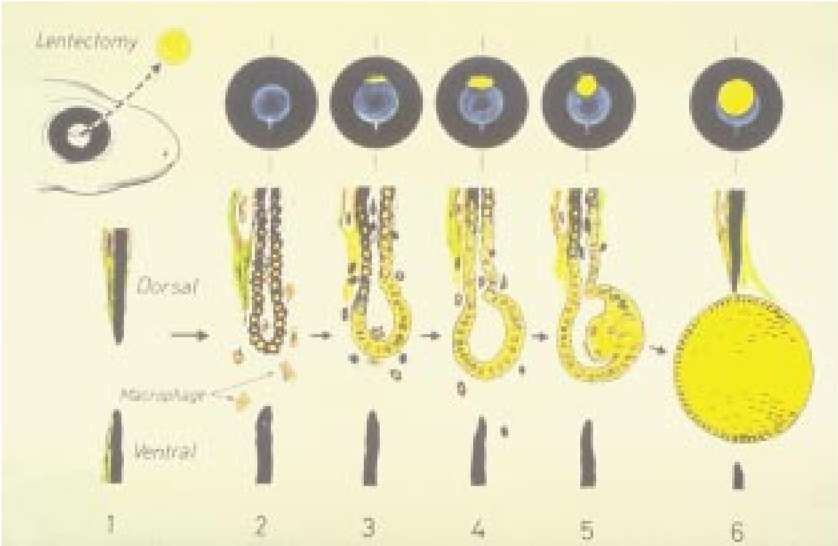
Jeremy Brockes

Jeremy Brockes, the MRC Research Professor at University College London, was a Caltech faculty member from 1978 to 1982. He has been given the Marcus Singer Award and a medal from the British Biological Council for his work on limb regeneration. He received his PhD from Edinburgh University.

I'm going to talk about what Barbara just called science fiction—using stem cells to regenerate whole limbs and tissues. As mammals, our abilities to do this are very circumscribed, with two notable exceptions—the regeneration of antlers in the male deer, and the regeneration of the liver. It's been suggested that an understanding of liver regeneration underlies the myth of Prometheus, who was cruelly punished by the gods by being chained to a rock while a bird devoured his liver by day, only to have it regenerate by night.

But even Prometheus's feat pales by comparison with the aquatic and terrestrial salamanders, who have the most remarkable regenerative ability among the animals that share our basic body plan. In the head alone, they can regenerate, with essentially perfect restoration of function, the upper and lower jaws and all of the ocular tissues—lens, retina, and iris. And the extremities—the limbs and tail—will regenerate as

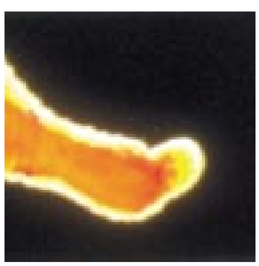
The arrows above point to just some of the body parts that a salamander can regrow with ease.



Left: This sequence of drawings shows what happens after a salamander's lens (yellow circle) is surgically removed. At bottom is a series of cross sections through the iris (black). Some of the black iris cells revert to stem cells, as shown by the color change, which then go on to form a new lens (the spherical structure), plus the muscle and connective tissue needed for it to function. This figure was kindly provided by Professor Goro Eguchi of Kumamoto University, Japan.

good as new, as will the internal organs, most notably the heart, which I'll mention later. Confronted with these feats, we tend to imbue these animals with an almost mystical ability. But this probably isn't the right way to look at regeneration. It's really very widespread among animals, and for reasons that are not understood, mammals have largely lost it. One argument for why we might have done so is that we traded it for the ability to heal wounds more rapidly.

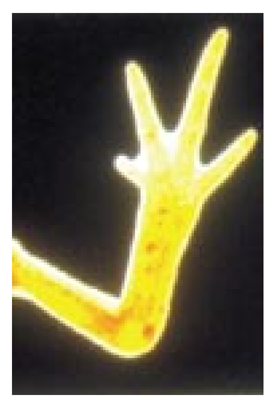
Salamanders regenerate tissues by turning differentiated cells at the site of injury back into stem cells—a strategy we would like to learn. The drawing above shows how it operates in the case of the lens. After the lens is surgically removed, the pigmented cells of the iris change their identity, start to divide, and a new lens grows downward to replace the old one. It's a remarkably efficient reaction. But what's most striking, of course, is the complete restoration of an amputated limb, as shown in this sequence of photos.

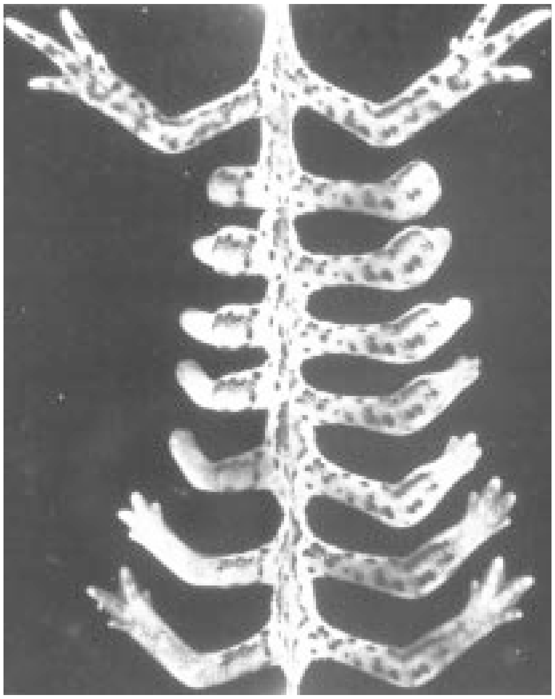


An amputated forelimb (above) grows back as good as new in 90 days (far right). Wish we could do that!

The animal generates a discrete population of stem cells—a growth zone, if you like—on the stump of the limb, and those stem cells reconstruct the missing appendage. This mound of stem cells, which we call a blastema, derives very important local cues for the function that it is going to perform. It's absolutely critical that the cells know to give rise just to the missing structures, whatever they are, and no more. So if the mound is at the shoulder, the stem cells somehow know to construct essentially an entire arm, whereas if they're closer to the wrist, they know to create only a hand. We don't as yet know what those cues are—what is it that cells derive from being at the wrist versus at the shoulder? Once the cells have been reprogrammed, the blastema has remarkable autonomy. We can cut it off and transplant it to, say, the tail fin, a region quite remote from the original limb, and it will still give rise to a perfectly normal limb. So we would obviously like to understand these processes, and manipulate them to our advantage.

The best we mammals can do along these lines is an experimental approach to bone repair based on stem-cell therapy. I have a colleague, Herve Petite, whose lab in Paris is deriving so-called mesenchymal stem cells from bone marrow and loading them into a scaffold that is positioned between the broken ends of a sheep's leg bone. (A newt can't repair such a gap in the bone.) The scaffold provides a mechanical guide of the appropriate shape, and also stimulates the mesenchymal stem cells to produce new bone that fills in the injury. Both functions are very important, and a lot of time and money goes into developing and evaluating new types of scaffolds for tissue engi-





Left: This is neither a coatrack nor some particularly appalling mutant cockroach, but two sets of composite pictures of a limb regrowing from the shoulder (left) and wrist (right). Below: The blastema is a tiny mound of cells, about 1.5 millimeters in diameter at the base. This one has been transplanted to the dorsal fin, where it will proceed to grow into a perfectly normal, albeit misplaced, limb. Photo kindly provided by David Slocum, Indiana University.

Above: A North American red spotted newt poses for the swimsuit edition of *Cell*.

neering. Interestingly, one of the most promising materials found so far is derived from coral. It's a natural matrix that is very good at stimulating stem cells to make bone.

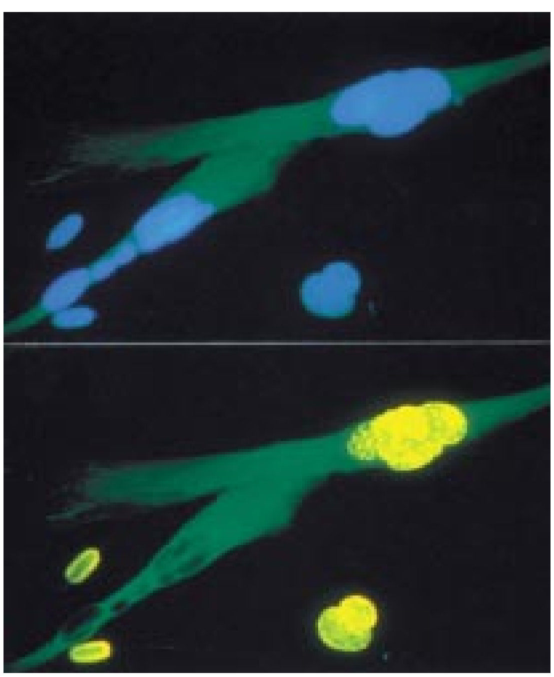
My lab studies the North American red spotted newt, which is a species of salamander, and I'm often asked, will we ever be able to regenerate like a newt? Unfortunately, there are so many layers of difficulty and uncertainty, so many things that we don't understand, that it's not possible to give a meaningful answer. When we're confronted with this sort of complex process, it helps to focus on particular parts of the mechanism that seem important.

I think a critical aspect of what the newt does is returning specialized cells to the cell-division cycle, which we mammals find very difficult to do. If you doubt in any way that this is important, let me reassure you with the example of the heart. Our ability to repair heart lesions is limited by the fact that our heart-muscle cells cannot respond to injury by dividing and generating more muscle. The newt, on the other hand, can respond to dramatic cardiac lesions by setting the cells around the lesion into division.

My lab studies this in the context of skeletal muscle, not heart muscle, but the principles are the same. Skeletal muscle arises from the fusion of cells with single nuclei (most cells have only one nucleus per cell) to give multinucleate muscle cells, which give rise to our muscle fibers. When this happens, our cells lose the ability to divide again. In fact, this is a general rule of differentiation—differentiated cells don't divide in response to the signals that caused their precursors to divide. But newt muscle cells can. At the bottom of the next page are two muscle cells from a newt.

The cell in the top photo has been stimulated to go back into the cycle of cell division, the first step of which is to duplicate the cell's DNA. That's indicated in the bottom photo by the fact that the nuclei are now yellow because they have taken in a fluorescent molecular precursor to DNA. Interestingly, we can fuse a newt muscle cell with a mouse muscle cell to obtain one cell that contains nuclei from both the mouse and the newt. And we find that if we stimulate the newt nuclei to enter the cell-division cycle, we stimulate the mouse ones as well. So whatever signal triggers the newt muscle to go back is also able, at least in this circumstance, to trigger mouse nuclei.

I'd like to end my talk on a personal note. I last spoke here 19 years ago, when I gave a public lecture on multiple sclerosis—one of the most mysterious and distressing of all the neurological disorders. (See "Nerve, Myelin, and Multiple Sclerosis," *E&S*, March 1982.) I was on the faculty here then, and I was working on a protein called glial growth factor that stimulated the growth of Schwann cells, which are the cells that form the insulation around your nerves and which are destroyed in multiple sclerosis. This factor has turned out to be very promising in stimulating the repair of the insulation, and in the last year, it's gone into clinical trials in human patients. These trials take three or four years, but it's been very rewarding to see that research come all the way to being tried for therapy. My hope is that the same will happen for our work on the newt and regeneration.



Alexander Capron

Alexander M. Capron is the Henry W. Bruce Professor of Law and the University Professor of Law and Medicine at the University of Southern California. He is a member of the National Bioethics Advisory Commission appointed by President Clinton, was chair of the U.S. Congress's Biomedical Ethics Advisory Commission, and before that was executive director of the President's Commission for the Study of Ethical Problems in Medicine and Biomedical and Behavioral Research under Presidents Carter and Reagan. He earned his LLB from Yale.

Ironically, using early embryos as a source of human ES cells turns out to raise more public-policy issues than using aborted fetuses.

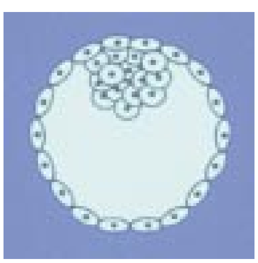
The stem-cell controversy came to public attention in November 1998 when, in the space of a few days, there were three publications—two in scientific journals and one in the *New York Times*. The first, in *Science*, announced that James A. Thomson and his colleagues at the University of Wisconsin had generated lines of human embryonic stem (ES) cells from a frozen embryo donated by a couple who had received fertility treatment. At virtually the same time, John D. Gearhart's team at Johns Hopkins University announced in the *Proceedings of the National Academy of Sciences* that they had derived a special kind of stem cell, called an embryonic germ cell, from fetuses aborted about six to nine weeks after conception. (At this stage, the tiny fetus is still known scientifically as an embryo.) These two scientific papers were followed two days later by a *New York Times* story that scientists at Advanced Cell Technology (ACT), a Worcester, Massachusetts, biotech company, claimed to have created stem cells by fusing human cells with cow eggs from which the DNA had been removed. (However, it has been a year and a half now, and this work has never appeared in a peer-reviewed journal, so we really don't know what they did.) Because of the human origin of the cells involved in these three cases, President Clinton immediately asked the National Bioethics Advisory Commission (NBAC), of which I'm a member, to undertake a "thorough review of the issues associated with such human stem cell research, balancing all ethical and medical considerations." And so within just eight days we went from the first scientific announcement to the beginning of the commission's inquiry.

The Wisconsin, Johns Hopkins, and ACT groups each used a somewhat different method to produce their stem cells. The early stage embryo (or zygote) used by the Wisconsin scientists came from a fertility clinic that had used in vitro fertilization (IVF), the uniting of egg and sperm in the laboratory to create a "test tube baby." In the first days after fertilization, the cells of the zygote are all totipotent, meaning that each one if separated could begin the process of creating an entirely new organism. (This is how identical twins are created.) The scientists at Wisconsin let the egg continue to develop for six to seven days after fertilization, until it took a form known as a blastocyst. A blastocyst resembles a balloon, on one part of whose inner wall is a clump of cells that are going to become the organism. (If the blastocyst were implanted in the uterus, as normally happens, the cells making up the balloon would become the placenta and the support structures for the developing organism.) Thomson's group cultured the cells from that inner cell mass to create a stable line of ES cells. Though no longer totipotent, these cells are still pluripotent: they cannot create a whole organism but they can give rise to all of the various specialized stem cells that are the origins of different tissues—bone, nerve, muscle, blood, and so forth. The ACT group also claims to have derived a human ES cell line from the blastocyst that arose when the fusion of a human cell with an enucleated cow egg cell caused the human cell to revert to pluripotency.

The other method, used by the scientists at Johns Hopkins, involved fetuses aborted at a stage in pregnancy when many women don't even know they are pregnant. Working through microscopes, the researchers went into these tiny entities to a structure called the gonadal ridge, which is made up of the cells that are migrating through the fetus to become the testes or the ovaries. These cells are called germ cells because they will beget eggs and sperm that can germinate into a new organism. These germ cells are still pluripotent, although they have gone a little farther down the developmental path than the blastocyst-derived cells.

PICTURE CREDITS:
16 — Bob Paz;
22 — USC

Looking at these developments, NBAC saw a number of issues. The central issue was whether such work should be funded by the federal government or only be privately supported. Private sponsorship would take most of the public-policy issues off the table, but if private industry were the only source of stem cells, we could end up with trade secrets and exclusive licensing agreements limiting what scientists could do with the resulting cells.



A blastocyst.

You might well expect that the greatest controversy regarding public funding would arise over research using fetuses aborted at six to nine weeks, as opposed to embryos frozen less than a week after fertilization, and indeed debates about the ethics of research with fetuses have been going on for a long time. In the 1970s, a national research-ethics commission developed a set of rules and requirements for research involving cells and tissues excised from dead fetuses. The major requirement was that such fetal remains must be donated in accord with state law, which is pretty much the same across the country, since every state has adopted the Uniform Anatomical Gift Act. That act established a set of procedures for donating transplantable organs after death. It also gives the next of kin—in this case, the parents of the fetus—the authority to authorize the donation. Donations are supposed to be just that: gifts. That was further ensured by the National Organ Transplant Act, which specified that donors cannot be paid.

In the 1980s, physician-researchers began to try transplanting fetal neurological tissue to treat Parkinson's and other neurological diseases. It was proposed to the Reagan administration that the federal government fund this work, but abortion opponents worried that this use of fetal tissue would cause women to have abortions, or even to conceive a fetus for the purpose of providing fetal tissue to a relative with a neurological condition. So the Department of Health and Human Services (DHHS) was persuaded to impose a moratorium on such funding and to appoint an advisory panel of experts to study the situation. The panel recommended that the work be funded, but the department, by then under President Bush, rejected the recommendation and continued the moratorium. Nothing was done, however, to stop such research in the private sector.

When President Clinton came into office, one of the first things he did was lift the moratorium. To ensure that this new policy was implemented appropriately, Congress looked to the report by that DHHS advisory panel for relevant safeguards. Thus when Congress enacted the National Institutes of Health (NIH) Revitalization Act in 1993, federal funding of research involving the transplantation of tissue from aborted fetuses was permitted, but restrictions were placed on the manner in which these fetuses could be obtained. Not only were strict rules enacted about information disclosure and donor consent, but rules were established to remove any incentives for women conceiving fetuses for transplant purposes or deciding to abort just to provide tissue for transplantation. Specifically, researchers were forbidden to pay for fetal tissues or to promise that donated tissue would be transplanted into a particular person.

The upshot is that procedures and standards actually do exist for federal funding of research in which ES cells would be derived from aborted fetuses. Indeed, the Johns Hopkins team could legally have received NIH funding for their derivation of embryonic germ cells from aborted fetuses. (In fact, they did not rely on federal funds, but had private funding sources, including Geron, the Menlo Park, California, biotech company that supported the Wisconsin research.) So the only possible reason for amending the present statutes might be to make clear that the present rules, which apply to the transplantation of fetal tissue directly to patients, also encompass the use of such tissue as a source for ES cells for further research and eventual therapy.

Ironically, using early embryos as a source of human ES cells turns out to raise more public-policy issues than using aborted fetuses, for a couple of reasons. First, taking the inner cell mass from a blastocyst ends the life of the embryo, whereas the gonadal-ridge tissue comes from aborted fetuses that are already dead. Second, the whole IVF field is in great ethical and legal disarray in the United States. It's worth noting that when IVF research began back in the 1970s, the British took quite a different approach. Their government appointed a body called the Warnock Committee—named for its chair, philosopher Dame Mary Warnock—which in 1984 recommended that IVF research be limited to the first 14 days of development, after which the embryos had to be destroyed. (Fourteen days is biologically significant, because it's before the embryo would implant itself in the uterine wall and before certain kinds of differentiation begin to occur.) Out of that came what was first a voluntary, and is now a statutory, licensing body in Great Britain. The Human Fertilisation and Embryology Authority (HFEA), which was set up in 1991, ensures that all licensed clinics that offer IVF or donor insemination, or that store eggs, sperm, or embryos, are inspected regularly and conform to high medical and professional standards. HFEA also licenses and monitors all human-embryo research, and serves as a forum for the debate that such research often stimulates. Because of its record-keeping requirements, the HFEA can actually keep track of how many embryos exist in all the labs and clinics in the United Kingdom.

The issue of supporting research on IVF actually received governmental attention in the United States before the Warnock Committee, but the results were less satisfactory. In May 1979, an Ethics Advisory Board set up by the Department of Health, Education, and Welfare recommended that the department should be able to fund IVF research under rules very similar to those later endorsed in the U.K. Yet in the U.S., the controversy that greeted this report was such that it has sat on the desk of any number of successive secretaries of what is now DHHS for going on 21 years. As a result we have no federal controls on human IVF research because the refusal to fund it at the federal level drove scientists who were working in this field to various sources of private money. Indeed, long before IVF was really ready for clinical application—or would have been used, had it followed the route of most research fields conducted with NIH support and leadership—a welter of private fertility clinics arose, where new procedures were tried out with patients' money.

We have no federal controls on human IVF research because the refusal to fund it at the federal level drove scientists who were working in this field to various sources of private money.

For a number of years, the limitation on federal support for research into IVF methods and other research involving the creation of embryos has been formalized through congressional riders to the appropriations bills for DHHS, which includes NIH. These riders provide that none of the funds in that statute may be used for research in which embryos are created, or for research in which they are "destroyed, discarded, or knowingly subjected to risks of injury or death greater than allowed for fetuses in utero." (Under federal research regulations, fetuses in utero cannot be exposed to any risk of substantial injury, except that necessary for their own benefit, which would obviously not apply to an embryo used in ES cell research.) In effect, federal funds cannot be used for the research whereby human embryonic stem cells would be obtained.

Plainly, government scientists—and many in universities, who are used to conducting federally supported research—want to conduct research using ES cells. The cells are viewed as enormously valuable—for basic research into cellular and organic development (including the biology of aging), for studies of drugs and other agents, and for therapeutic research, especially that which aims to control cellular development and to create replacement tissues (and perhaps even organs) genetically matched to the recipient. Does the rider absolutely prevent such research from receiving federal funds? NIH put this question to Harriet Rabb, general counsel of DHHS, who concluded that the restrictions do not apply to research *utilizing* human ES cells, for two reasons. First, "such cells are not a human embryo within the statutory definition"—being pluripotent, rather than totipotent, they cannot develop into a whole organism. Second, using an established ES cell line does not directly involve the destruction of an embryo. Therefore, NIH said it would fund research using, but not the research necessary to obtain, human ES cells. NIH established an ad hoc panel that prepared a set of rules for applying for federal funds for research with human ES cells that focused in large part on ensuring that the cells were obtained according to prescribed ethical standards. Many members of Congress vigorously protested this as a misinterpretation of their intent, while the American Association of Medical Colleges and other scientific groups strongly supported NIH's position.

Meanwhile, NBAC has concluded that it is intellectually indefensible to say that a statute intended to prevent federal funding of research in which embryos are destroyed would allow funding of research using the products of that process. It's obvious that when NIH funds go to a research group using stem cells, some of that money is going to go to the scientist in that group who's creating the cells to be used. We also thought, for scientific reasons, that it would be far superior to confront the issue. If you artificially separate the process of deriving the cells and the process of using them, the scientists who use them cannot be directly involved in the method by which they are derived. Especially at this early stage of a field involving so many unknowns, how the cells are derived may turn out to have a great impact on how they behave and what can be done with them. So it would be natural—and scientifically preferable—for the scientists using ES cells to work closely with those deriving them.

NBAC's findings, released last September, concluded that two methods for creating human ES cells were acceptable. The first was to use aborted fetuses. This means induced abortions—spontaneously aborted fetuses are not a very good source, because a woman who spontaneously aborts at that developmental stage is usually unaware that she was even pregnant, much less that she has miscarried, making it nearly impossible to recruit such donors or to recover the fetuses. And as mentioned before, aborted fetuses are already an acceptable source of tissue for research, under federal regulations that impose strong consent requirements, separate the research process from the decision to abort, and prohibit any financial incentives that would lead the doctor or the woman to decide to have an abortion. The second acceptable source, we felt, was to use existing embryos from in vitro fertilization that have been frozen for some future pregnancy attempt. (In recommending that the prohibition be lifted on this specific category of embryo use, we did not address the general ban on embryo research.) The same strong consent requirements, separation from the research process, and ban on financial incentives that apply to fetuses should be erected here. Indeed, we argued that these embryos should only be made available after a couple has decided not to continue trying to get pregnant this way (or has decided that they have all the children they want to have) or after a particular embryo has been found to be unsuitable for implantation. This has since been proposed by Senator Arlen Specter, Republican of Pennsylvania, and Senator Tom Harkin, Democrat of Iowa, whose bill is now before Congress.

Nonetheless, we felt that it was not appropriate at this time for federal funds to be used in creating embryos specifically for research. First, there doesn't seem to be any need—there are hundreds of thousands of frozen embryos in storage; many, many more than would be needed to establish plenty of ES cell lines. Second, the possibilities for abuse are much greater, and the discomfort of many people with the prospect of starting a human life with the intention of ending it argues for restricting public funding. Of course, even under the regime we proposed, fertility clinics could intentionally create excess embryos. The best protection there, of course, would be to prohibit financial incentives and ban commerce in these embryos. Finally, we did not think it was appropriate, at this time, to make embryos from somatic-cell nuclear transfer—the process that gave rise to Dolly the sheep. Both the underlying cloning technology and the ability to get stem cells to differentiate into tissues and organs are still too rudimentary: this is a bridge we just don't need to cross right now.

It is intellectually indefensible to say that a statute intended to prevent federal funding of research in which embryos are destroyed would allow funding of research using the products of that process.

Some opponents of using ES cells have suggested that pluripotent cells should instead be derived by inducing differentiated adult cells to regress to a pluripotent state. (This would be somewhat similar to the research that Jeremy described.) It would avoid the need to create new embryos, and it could produce specialized tissues for autologous transplantation without resorting to somatic-cell nuclear transfer. Thus, this means of deriving pluripotent stem cells is very attractive, and work in this field deserves to be pursued and supported. But the research is still too preliminary, and the theoretical and practical barriers too great, to make it prudent to abandon research on deriving pluripotent stem cells from embryos and fetal tissues.

Three of our other recommendations bear particular emphasis. First, we urged ongoing oversight; any research using human ES cells should have to be approved by a review panel. Second, the protocols for deriving the stem cells should be reviewed by an Institutional Review Board, which is a research-ethics committee at the institution doing the work, to ensure compliance with requirements that would be established nationally. And finally, private sponsors of such research would be wise to adopt these same recommendations voluntarily, including submitting their protocols for deriving human ES cells to the national panel for review and certification. □

PICTURE CREDITS:
26, 28, 29, 35 — Hugh Davies; 29, 36 — USC Tsunami Research Group; 28, 34 — Emile Okal; 30, 32, 35, 36 — Phil Watts; 31, 33 — Dave Tappin; 33 — JAMSTEC

Of Landslides, Couch Potatoes, and Pocket Tsunamis

by Douglas L. Smith

A fifteen-year-old boy from Arop No. 2 village points out the palm tree he climbed to escape the wave, which came up to just below the fronds. (When villages adjoin one another, they frequently have the same name and are distinguished by numbers.)

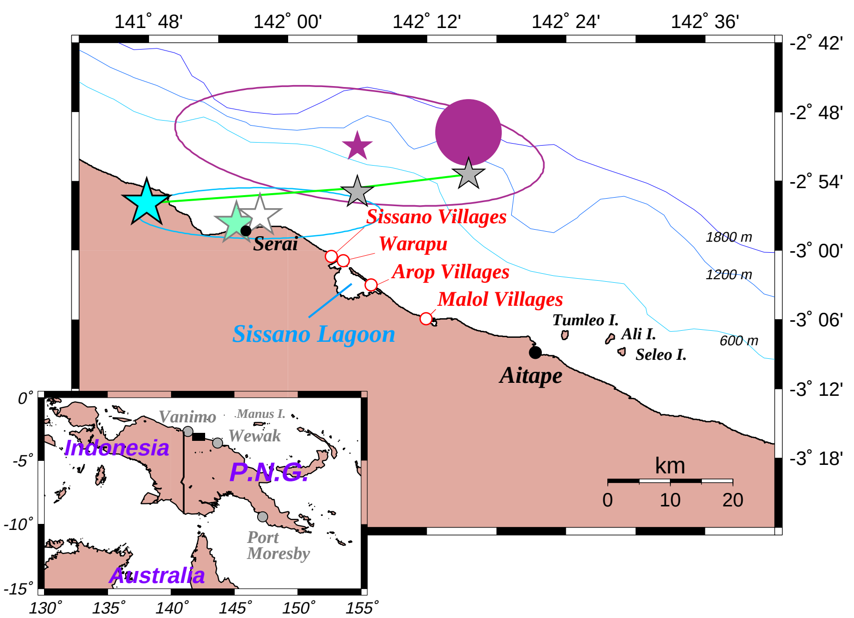
Sometime after seven o'clock in the evening on Friday, July 17, 1998, a wall of water three stories high wiped out a 25-kilometer stretch of tropical paradise on the north shore of Papua New Guinea. Hardest hit was the Sissano Lagoon region, where three villages of thatched huts sat on the spit of sand that divided the ocean from the lagoon. The tsunami, which penetrated as much as three kilometers inland in other places, washed over this glorified sandbar like it wasn't even there. All three villages were completely destroyed, and several more up and down the coast were heavily damaged. At least 2,200 people died, and some 12,000 souls were left homeless as buildings were swept away like yesterday's sand castles—even substantial structures, such as churches and schools, were reduced to their concrete-pad foundations. This tsunami, which actually consisted of three separate waves, is making waves in the scientific community as well, as it bolsters a theory advanced by a group of Caltech alumni that some of the largest localized tsunamis are caused by underwater landslides instead of by the motion of the seafloor during an earthquake.

The tsunami followed a magnitude 7 earthquake at 6:49 p.m., and earthquakes frequently *do* generate tsunamis. Such tsunamis are called tectonic, and their size is related to the energy released by the quake, which is readily derivable from seismograms. Tsunamis also travel at known speeds, so their arrival time at any location can be calculated. And that was the problem with this one—like a typical Hollywood disaster movie, it was late (by a full 10 minutes) and waaaay over budget. The standard tectonic-generation models predicted that the wave should have been, at most, 1.3 meters high on arrival—about average for the surf there. So what happened? How did this two-bit tsunami become a killer wave, and what took it the extra 10 minutes? As Chief Engineer Montgomery Scott is fond of saying, "You canna change the laws of physics," so unless there's some sort of time-dilation effect worthy of a *Star Trek* episode going on here, whatever caused the tsunami must have happened after the earthquake.

Well, earthquakes also unleash landslides—sometimes hours after the shaking stops. In a 1982 study of the 1980 Mount St. Helens eruption, Hiroo Kanamori, the Smits Professor of Geophysics, and Jeffrey Given (PhD '84) concluded that the massive landslide that uncorked the eruption had a distinctive seismic signature. Then, in 1987, Kanamori and H. S. Hasegawa of the Geological Survey of Canada examined seismograms from the 1929 Grand Banks earthquake (magnitude 7.2), which caused a tsunami that killed 27 people on the south coast of Newfoundland, and found the same signature. A landslide had been suspected there long before Kanamori's time, because the spiderweb of transatlantic telegraph cables had snapped in 28 places. The breaks' timing helped map the slide's path—there were 14 "instantaneous" ones within 100 kilometers of the epicenter, followed by a series that rolled downslope and across the abyssal plain, with the final one coming some 560 kilometers away and 13 hours 17 minutes later. Since then, a half-dozen or so other tsunamis have been convincingly linked to landslides as well. This notion sloshed over to Caltech's engineering and applied science division, where Philip Watts (PhD '97), working with Fred Raichlen, professor of civil engineering and mechanical engineering, derived a computer model of waves generated by a submerged landslide. This model, based on wave-propagation code developed by Stéphan Grilli of the University of Rhode Island, was the first to take a user-defined motion of the landslide's center of mass to represent the motion of the landslide as a whole, a feature that would eventually prove to be crucial.

Most tsunami models start with a source motion on the seabed. The most common is an earthquake that instantaneously dislocates the

Just an average day in paradise. The house in the background is typical of local construction methods. The posts on which it rests are driven two or three feet into the ground. This photo is of a resettlement village built for the survivors from the Arop villages. In the foreground, USGS geologist Jocelyn Davies swims with some village kids.



The large map shows the tsunami area (the black rectangle in the inset map). The villages labeled in red were devastated or partially destroyed, while the ones in black escaped serious damage. Stars indicate the epicenters of some significant earthquakes. Papua New Guinea doesn't have many seismographs so the locations are imprecise—the three large stars in the blue error ellipse are all putative main shock locations, with the white star being the one the Caltech group calculated. The two gray stars are the pair of aftershocks, and the green line behind them is the fault. The purple star is the mysterious 7:02 seismic event; its error ellipse, also in purple, includes the landslide (purple circle).

water above it to create a wave. This is why tsunamis pack such a wallop: in deep water, all the kinetic energy of a wind-generated wave lies within a few wave heights of the surface, but a tsunami goes all the way down—the entire water column is in motion. When all this energy gets squeezed into a few meters of shallow water, all hell breaks loose. Conventional tsunami models assume a tectonic source—a block of seafloor is thrust up, in the Papua New Guinea case by about 40 centimeters, and the tsunami is born as the water collapses back on itself. But a landslide on the move leaves a void behind itself that the ocean instantly fills, creating a wave.

A computerized tsunami is really three separate models: source, propagation, and arrival. Once the wave has been generated, by whatever means, it spreads through the high seas according to the laws of fluid mechanics, which were translated into a form appropriate to tsunamis by Joseph Hammack (PhD '72) and Jiin Jen Lee (PhD '70). Then, as it nears the coast, the wave's detailed behavior depends on the topography, both above and below the shoreline. The tsunami's run-up, as it's called, is the province of Costas Synolakis (BS '78, MS '79, PhD '86), who first suggested the approximations needed for computer simulations while modeling run-up under Raichlen and is now a professor of civil and environmental engineering at USC and director of the tsunami center there.

But neither the tectonic nor the landslide models' predictions of wave heights and arrival times matched the maps and measurements made by the International Tsunami Survey Team. The team was cosponsored by the National Science Foundation, the Japan Science Foundation, and the Ministry of Science and Culture and co-led by Synolakis, who has been on nine such teams in seven years, and Yoshiaki Kawata of the Disaster Prevention Research Institute at Kyoto University. The survey found that the wave height fell off very rapidly outside the zone of inundation, leaving

Paradise leveled: This was a small, unnamed hamlet east of the lagoon mouth. The angled logs in the foreground used to be house posts. The silver object high in the tree is a bucket left there by the wave. At right, survivors from Arop No. 1 stand in the scour left by the wave—note the scarp in the background.

Left: Some survey team members set out for the next village. In the bow are Costas Synolakis (wearing vest); seismologist Emile Okal, PhD '78 (with hat); and José L. Borrero, a field surgeon and father of Synolakis's grad student José C. Borrero, who was also on the team.

villages just a little further up or down the coast completely untouched. But a tectonic source takes impetus from the entire length of the rupture (about 35 kilometers for a magnitude 7 quake), so its effects are felt along a very broad front. And as this quake is believed to have started about a kilometer or two offshore and headed out to sea at a shallow angle, a tectonic tsunami should have trashed a much larger area if it trashed anything at all. Even stranger, the shore closest to the epicenter got a wave only a couple of meters tall. (The epicenter's location is not very precise, as that part of the world isn't heavily instrumented—we're spoiled here in Southern California.) The landslide model fared better in that a landslide is a more concentrated source, so its effects are highly localized and an intense "pocket" tsunami, if you will, is a likely outcome. But still, the numbers just wouldn't come out right. If this was indeed a pocket tsunami generated by a landslide, the computer models were missing an essential feature.

The survey team visited the area two weeks after the disaster. It's important to get there fast, Synolakis explains, especially during the rainy season—one good storm can wash away the high-water marks, and obliterate the debris paths that tell you the wave's angle of approach. There were no buildings left on which to measure lines of discoloration from the flooding, but the trees told their own eloquent story: some were stripped clean of branches to a height of 12 meters; others had household goods and wreckage lodged in their tops. "If you have a severe wind, that bucket in the tree would just fly away," he says. "And people scavenge things. The lagoon villages are inaccessible by road. They can't just go to the store and get another bucket, so if you wait too long they will have combed the area and picked up everything that they can reuse. And eyewitness accounts change: as time passes, people start hearing the story from the local authorities or the shortwave radio, and it contaminates their memories. They are more likely to give you the official number than what they actually saw. They hear, for example, that 'it was a 40-foot wave and it came from the north,' and that's what they'll tell you. But then when you ask them to point to where they saw it go, you get different results."

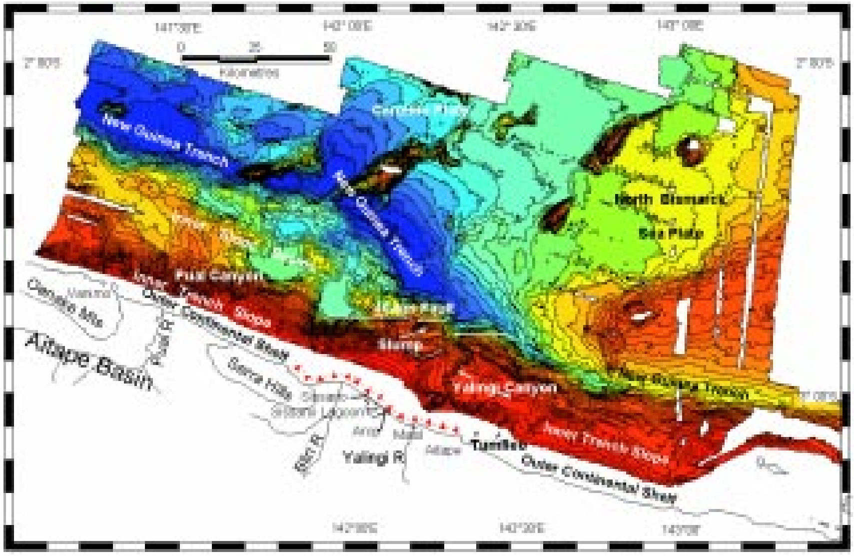
In more built-up areas, automatic tide gauges—rugged instruments mounted in concrete—would have recorded the waves' arrival times. (If nothing else, you could at least note the time when the recording stopped.) Here, the team had to rely on people's memories. Hugh Davies, professor of geology at the University of Papua New Guinea, in Port Moresby, spent every weekend for six months afterward interviewing survivors, many of whom had been dispersed to hospitals or resettled in new villages farther inland. When he quizzed people about the time of arrival of the wave he was given many different answers. "That's what you

Above: Launched in 1997, the RV *Kairei* is designed to stay at sea for months at a time. She's 105 meters long overall, displaces 4,628 gross tons, and has a crew of 29—not counting up to 31 scientists. The big blue thing is an A-frame designed to lower corers, sonar arrays, or even robot submarines. Below, left: Pirates are a big problem in the South Pacific, so the *Kairei* sported a barbed-wire girdle when not in port. Fire hoses and stacks of bamboo staves were kept ready at all times to repel boarders. Below: These guys weren't exactly pirates, but they may have been smugglers—they approached the ship expectantly, says Watts, but eventually left when nothing was thrown overboard for them to retrieve. Whatever they were, they were bold seafarers—the *Kairei* was roughly 100 kilometers from the nearest land at the time.

expect when people mostly measure the time of day by the sun," says Jocelyn Davies, a physical science technician at the United States Geological Survey's Pasadena office. Davies, who lived in Papua New Guinea until she was nine, flew back twice after the disaster and assisted her dad with follow-up interviews. "In Aitape [a larger town at the fringe of the devastation, where the wave was only three meters tall], they could at least tell us that the wave came ashore a few minutes after the seven o'clock news started on TV." Otherwise, the best one could hope for was to get information on the sequence of events: Did the wave hit before or after the big aftershock? If the interviewee said, "What aftershock?" it was presumed that the tsunami arrived at the same time or earlier, monopolizing the person's attention. (The aftershock, which was widely felt, occurred 20 minutes after the main shock and was actually two shocks—a 5.6 and a 5.9 within 30 seconds of each other.)

The survey team noted many landslides on shore, and speculation arose that the tsunami might have been triggered by an offshore one. But the critical geology was under water, so the Papua New Guinea government issued an international request that a marine survey be done. It was a matter of some urgency—Papua New Guinea lies on an active subduction zone, where the Australian plate is riding up over oceanic crust. Earthquakes and their resulting landslides are frequent, so if the tsunami had in fact been triggered by a slide, were there other undiscovered hazards lurking offshore? Such programs usually take a year and a half to mount, but this one was organized in record time by close collaboration between the Japan Center for Marine Science and Technology (JAMSTEC), the South Pacific Applied Geoscience Commission (SOPAC), and the government of Papua New Guinea. The cochief scientists were Takeshi Matsumoto of JAMSTEC and David Tappin of the British Geological Survey, acting for SOPAC. (If you're wondering why an Englishman from Nottingham was representing SOPAC, it's because Tappin has been a marine geologist for 27 years, 17 of them in the South Pacific, including a five-year stint as the chief geologist for the Kingdom of Tonga.) In December 1998, JAMSTEC's RV (research vessel, not recreational vehicle) *Kairei* arrived, carrying an international team of 22 scientists from assorted disciplines, to try to get to the bottom of things.

There have now been four cruises on different vessels, and a fifth is planned—the first time that an undersea earthquake has ever been studied so intensively. Still, you can imagine what a disadvantage seismologists working on, say, the Landers quake would have labored under if they had been confined to an airplane flying a mile overhead while trying to figure out how much and which way the fault moved, and what kind of material it cut through. And we have better maps of the moon, Mars, and Venus than we do of much of



Left: The seafloor as surveyed by the *Kairei*. The Yalingi River's submarine canyon is shown, as is the slump (white arrow), which lies on the eastern side of the amphitheater (white arc). The amphitheater lies at the edge of a shallow shelf that extends out to sea from the lagoon. The colors indicate depth, from 200 meters (dark red) to 4400 meters (dark blue). The white zone just offshore is water less than 200 meters deep—too shallow for an oceangoing vessel as big as the *Kairei* to navigate safely in this ill-charted region. The red triangles show the stretch of coast where the tsunami was observed. The "40-km fault" was not the source of the magnitude-seven quake, but had been favored as a source of the tsunami. Bathymetry data courtesy of JAMSTEC.

Earth's ocean bottoms, so there was precious little prequake data to go on. But the *Kairei*, a spanking new ship with state-of-the-art multibeam sonar arrays accurate to half a percent of the water depth, (10 meters in two kilometers of seawater), provided great postquake data. Watts and several Japanese tectonic-source colleagues went along to provide modeling support. While the geologists were looking for faults and landslides, the modelers were compiling a comprehensive depth profile—bathymetry data, it's called—to feed into their various tsunami models.

A tsunami's height and arrival time are profoundly influenced by the water's depth. As the bottom shoals, the water piles up and the wave slows down, so an uneven seafloor will refract and reflect the wave, occasionally aiming it at a piece of shoreline like a lens focusing a searchlight's beam. The depth at which the bottom begins steering the wave depends on its wavelength, so for wind-driven waves a few meters apart, only the shallows count. Tsunamis, however, have wavelengths of tens to hundreds of kilometers, so it's *all* shallow water to them—the midocean abyssal plains average about four kilometers deep. The *Kairei* discovered a shallow shelf and a submarine canyon that helped focus the wave's energy toward the lagoon, but this boost still left the tectonic models severalfold short of delivering the observed run-up.

To trace the tsunami's point of origin, you run the model backward, and Watts recalls that on one mapping leg "I realized we'd be passing over what seemed like the most promising site at about 1:00 a.m. So I got up and watched the bathymetry come in—a 3-D color image being plotted in real time on the control console. And suddenly, amid the geologically old features—rolling hillsides and ancient reefs covered in sediment—we had a very sharp, several-hundred-meter-high cut, which turned out to be the scar from a slump." The slump proved to be about four kilometers wide by five kilometers long. It's part of a much larger amphitheater some 10 kilometers wide, the sum of many slumps over the eons. "That tells us that this is a very vulnerable area," says Watts. "We know there's enough sediment to fail again at the next earthquake. This is an important observation. Should the people move back into their old village sites? And the answer is an emphatic *no!* This is a very dangerous chunk of shoreline."

But what was down there? What kind of material gave way so catastrophically? All a dry-land geologist needs for sample collection is a rock hammer. But when your sample is at the wrong end of 1.5 kilometers of salt water, you need something more—in this case, a 10-meter length of pipe called a corer. Inside the pipe is a piston that starts out flush with the pipe's bottom end. The corer is lowered until the piston rests on the seafloor and a trip line releases the lead-weighted pipe, driving it down around the piston and cutting free a core. The effect is the same as sucking liquid into a straw, except that the straw moves instead of the liquid. The piston, now at the top of the pipe, acts like a thumb over the top of the straw and keeps the sample—even loose sand!—from falling out en route to the surface. And just to be sure, there's a "core catcher" at the end, which closes like the iris of a camera.

"And so on the fourth-to-last day of the science phase of the cruise Toshi Kanamatsu dropped our first core, and pulled out seven meters of really stiff clay. But all the models, including ours, assumed that underwater landslides were happening in a relatively thin layer of sand or silt. Sand moves. It's known to liquefy during earthquakes, and it's known to move hundreds of kilometers out onto the ocean floor when it lets go." In the nightly meeting of all the scientists to discuss the day's results, Tappin pointed out that clay would behave much differently. So upon returning Stateside, Watts asked soil mechanician Jean-Pierre Bardet (MS '79, PhD '84), now also a

Above: Somewhere at the end of that cable is the corer.
Right: Retrieving it is an all-hands operation.
Far right: Once it's safely on its dolly, principal JAMSTEC sedimentologist Kanamatsu (in profile) detaches the weighted piston before extracting the core from the pipe in an on-board lab. Wilfred Lus, who was born in nearby Wewak and is now a grad student in geology at the University of Papua New Guinea, looks on.

professor of civil and environmental engineering at USC, to describe clay's behavior mathematically.

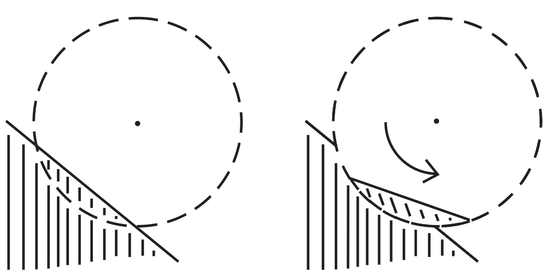
Says Bardet, "These hydrodynamic tools, these models, do marvelous things, making waves go all across the ocean, but the initial motion all depends on the mechanics of the source, which the models don't consider. It's just assumed. But when you are dealing with a local secondary rupture, like a soil failure, it's a much broader venue." In other words, there are a lot more possibilities to consider—a wider range of material strengths, more different types of failure modes—than just the snapping of pressurized rock deep underground. So Bardet analyzed a typical clay's shear strength to determine how much force it would take to set the slump in motion and how it was likely to move once under way.

It turns out that stiff clay moves in a "slump," not a "landslide," and this semantic nicety is of utmost importance. "A slump is like a couch potato," Watts explains. "When the slump fails, its butt slides a little farther forward on the sofa cushion, and its head sinks a little lower."

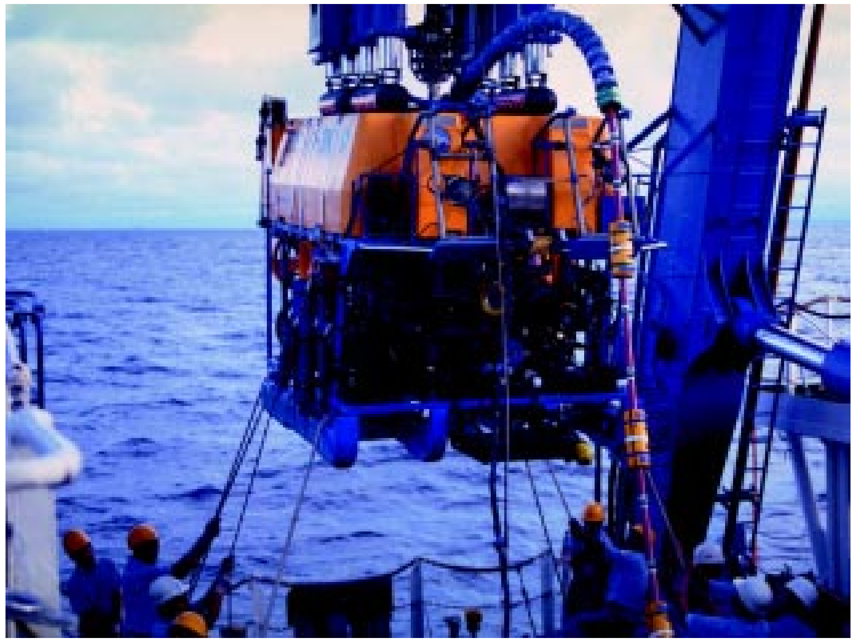
That is, the slump's center of mass moves down and forward in a short arc. This motion is modeled by rotating a cylinder that lies on its side on the seabed like one of the fallen columns of Atlantis. The cylinder penetrates the hillside (shaded) to a depth equal to the maximum thickness of the slump, and the buried portion of the cylinder's curved surface is the failure plane along which the slump will move. If you rotate the cylinder maybe six degrees, the embedded portion travels downslope a ways, and that's the slump. The degree and speed of the rotation, the diameter of the cylinder, and the depth to which it is embedded, all depend on the clay's shear strength.

Says Watts, "The key difference between a landslide and a slump is the center-of-mass motion. A slump starts and stops—if you plot position as a function of time, it accelerates, achieves some maximum velocity, and then decelerates. Whereas a landslide is like your umbrella getting whipped away by the wind and carried down the street—there's nothing to stop it. It experiences a relatively rapid acceleration, and then just keeps on going. *Nothing* stops a landslide."

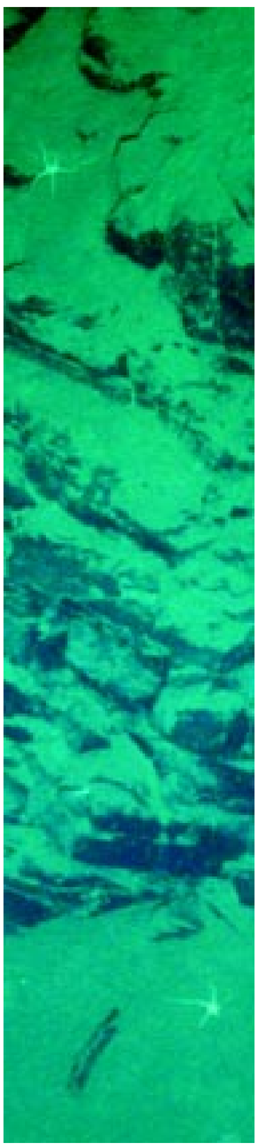
In January 1999, another JAMSTEC ship, the RV *Natsushima*, took over. *Natsushima* carries an unmanned submersible named *Dolphin*, whose cameras confirmed that the clay was stiff—there were knife-sharp fractures in the clay deep and wide enough to stand in—and that the slump was fresh, because the chunks that had detached themselves from the headwall at the top of the slump and tumbled downslope had not yet accumulated a blanket of sediment. The *Dolphin* also visited the stretch of fault that the tectonic modelers favored, hoping to find similar evidence of fresh activity. Recalls Watts, "We got an hour of what looked like a helicopter ride through the snow-

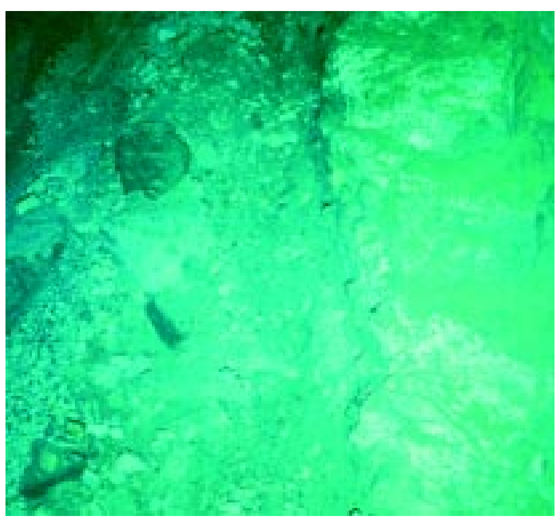


Above: A cross-section of a slump (not to scale).



Right: The *Dolphin.*





Above: This fissure is about two meters deep, three meters wide, and 50 meters long. Right: The debris flow on the left side of this photo is fresh, free of the sediment that covers the limestone cliff on the right. Left: A couple of starfish go about their business along an old, sediment-draped portion of the 40-kilometer fault scarp west of the amphitheater. Seafloor photos courtesy of JAMSTEC.

covered Alps. It was beautiful. It was stunning. Nobody moved, everything came to a halt. There were video monitors all over the place, and the ship was nothing but full of people staring in awe at these underwater mountains." But the snow was actually sediment, indicating that nothing had moved there in quite a while. Other *Dolphin* excursions found fresh faulting, but only off to the west, away from the tsunami's calculated point of origin. Says Tappin, "This is how mapping the seabed with multibeam bathymetry, and direct observations from remotely operated vehicles allow you to discriminate between tsunami source mechanisms."

A third cruise, sponsored by the National Science Foundation, took place in September 1999 (a more usual time lag for marine geology) aboard the Lamont-Doherty Earth Observatory's RV *Maurice Ewing*. On this voyage, seismic reflection studies by Eli Silver and Suzanne Sweet of UC Santa Cruz confirmed that the clay had moved cohesively, and gave the slump's maximum thickness as 700 meters. Reflection studies bounce shock waves (in this case, from an air gun) off the seabed and the sedimentary layers and fault planes that lie beneath it. The echoes are picked up by an array of hydrophones and processed by computer to give a cross-sectional view of the sea bottom.

But finding a fresh slump wasn't enough—did it cut loose at the right time? There were no undersea cables to sever—no smoking gun, in other words, but it turns out there *was* a gunshot. A U.S. Navy hydrophone near Wake Island, 3,600 kilometers away, picked up an unusual rumble at 7:42 p.m. Papua New Guinea time, or about 13 minutes after the quake, allowing 40 minutes for the sound to propagate through the ocean. The amphitheater proved to be a speaker pointing at Wake Island, which is a tiny pimple in the middle of the Pacific.

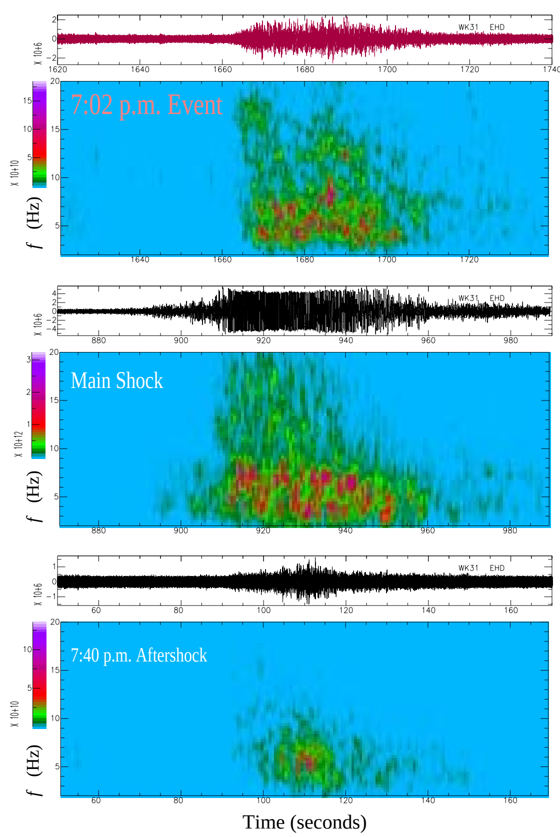
Seismologist Emile Okal (PhD '78), now a professor of geological sciences at Northwestern University, initiated the hunt for the vital recording. "I've been working with T waves for a long time, so when it became obvious that this event didn't fit any of the tectonic models, it was natural for me to look at the T-wave records. T waves provide sensitive detections of very faint sounds at extreme ranges: the Navy hunts subs, biologists listen to the love songs of whales, and geologists discover underwater volcanoes—I've found several, myself." T waves are trapped in a natural waveguide: as you go deeper, the pressure increases, which increases the speed of sound. But at the same time, the temperature decreases, which slows sound propagation, and the tug-of-war between the two means that there is some depth at which the speed bottoms out. Sounds entering this zone are trapped there, refracted back into it by the faster-conducting layers above and below. It's fiber optics for sound waves, basically. The depth of the SOFAR channel, as it's called, varies with latitude, but in the mid-Pacific it's about 600 to 1,800 meters down. At 1,500 meters, the slump lay at just the right depth to be heard.

Although the rumble coincided with an event listed as a magnitude 4.4 aftershock, it didn't look like any ordinary earthquake. Quake T waves fit a very standard pattern: they start abruptly and rapidly die off, with the signal's duration related to the earthquake's magnitude. A magnitude 4.5 aftershock at 7:40 lasted about 15 seconds; the 7:02 event went on for a good 45—almost as long as the main shock. And the 7:02 event gradually crescendoed, then even more slowly faded away—quite reasonable behavior for a slump that gathered momentum before petering out. When Okal did a spectral analysis—breaking down the signal to see how much energy was being carried at each frequency—things got even less earthquake-like. He explains, "Normally, you find the high frequencies, which correspond to fast energy release—ground motion at high velocity—at the beginning. But here, the frequency rose with time, indicating that the source was accelerating. The largest burst of energy is halfway through the signal, which is exactly what a slump does. Kanamori and Given first described this acceleration-peaking-deceleration behavior in their Mount St. Helens paper, and Kanamori and Hasegawa described it again later in their Grand Banks paper."

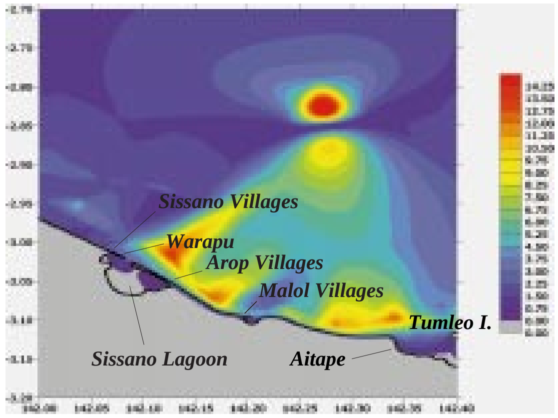
Hydrophones are submerged buoys containing microphones, anchored to float in the SOFAR layer. They're complicated and expensive pieces of equipment, and most of them belong to the world's navies. Thus their data are routinely classified. (The Wake Island records had been declassified as part of the prototype monitoring system for the Comprehensive Nuclear Test-Ban Treaty, and were at that point directly accessible from a Web site.) Fortunately, when T waves hit shore, they become easily recorded seismic waves. Says Okal, "seismometers near the seacoast will pick them up, and even humans will if the waves are strong enough. The Alaskan Panhandle quake of 1958 and the Bolivian earthquake of '94 were both felt by people in Hawaii."

So Okal turned to T-wave seismograms from stations scattered around the Pacific, and found something else unusual—a station in Taiwan picked up the main shock loud and clear, but the 7:02 event didn't register. Taiwan is roughly perpendicular to the speaker's beam line, in the acoustic shadow of the amphitheater's western wall, and apparently was out of earshot. In fact, the 7:02 event's T waves only showed up at a handful of stations.

Intrigued, Okal then reexamined the actual seismic-wave (not T-wave) records for the 7:02 event. There weren't that many, because a



The Wake Island T waves and their spectra (blue backgrounds) of the suspected slump (top), the main shock (middle) and a magnitude 4.5 aftershock (bottom). In the spectral plots, the redder the color at any point, the more energy is being carried at that frequency at that moment. The slump signal's high frequencies reach maximum redness toward the middle of the event, which lasts much longer than an aftershock of comparable magnitude.



Above: The slump model's predicted maximum wave heights in meters, time-averaged until just before impact. Waves are refracted toward shallow water and away from the deeps, so the shelf focuses the wave on Sissano, creating the large red region aimed at the lagoon. The Yalingi River canyon comes ashore at Malol and also steers the wave toward the lagoon, helping protect Malol, which was only partially destroyed.

A couple of concrete slabs and a cistern are all that remain of the Arop No. I village church, now a makeshift graveyard.

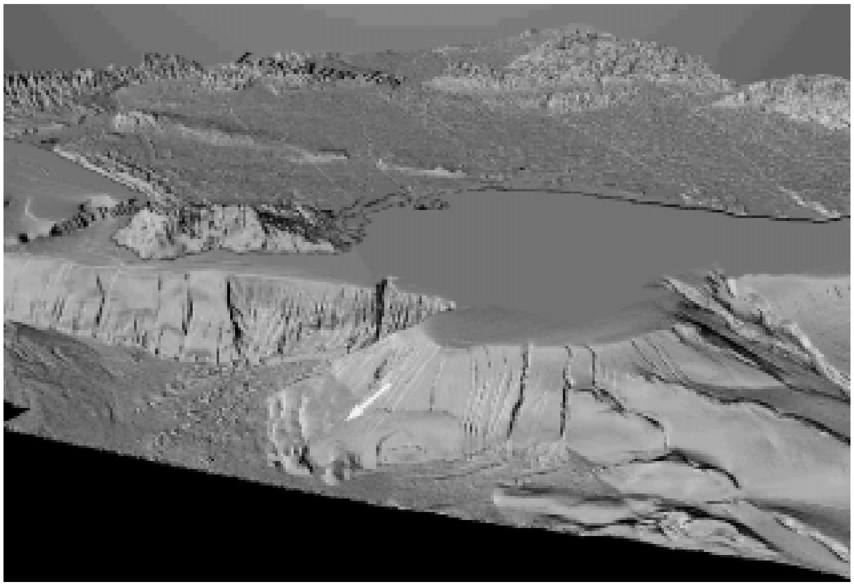
magnitude 4.4 isn't that big, and there were very few seismic stations close enough to catch it. Even so, he says, "I've derived a location ellipse from those few records, and it includes the amphitheater. Here was the proof that some activity took place 13 minutes after the main shock, at the exact location of the slump mapped by the *Dolphin*."

Run-up modeler Synolakis says the survey team's fieldwork adds one final tidbit in support of the slump model. "For many years, it's been standard, in fact universal, to model tsunamis as leading elevation waves—the crest in front of the trough. People thought that leading depression waves, trough before crest, were hydrodynamically unstable. Everyone was looking at the effects of tsunamis far from their sources, and it was thought that leading depression waves wouldn't propagate that far. But the Nicaraguan tsunami of '92 showed that subduction zones can produce tectonic tsunamis with depression waves, and if you look at the coastal manifestation of a tsunami close to its source, they turn out to be quite important. The slump model automatically provides the sense of the leading wave, which in most cases turns out to be a depression wave." The slump creates a void behind itself that the water rushes into, so that if it's moving toward deeper water the depression wave points toward land. "So finally we have a model that corroborates eyewitness accounts. In every tsunami in the past eight years, people always say the sea withdrew first, and then the wave came. Before Papua New Guinea, we could only try to explain this in terms of tectonic tsunamis, but now we know why. Unfortunately, the model shows that if you put the trough first, you get double the run-up than if you put the crest first." Adds Watts, "The other thing is, you have a bit of warning. If you see the sea receding, get out and stay out!"

This last bit of knowledge is paying off, says Synolakis. Last December, another pocket tsunami wiped out the village of Bai Martele in Vanuatu, formerly the New Hebrides. "The wave was eight to nine meters high, and in a village of that size there could easily have been two or three hundred people killed. But only three people died. Why? The magic of television. They have no electricity, no water, no nothing, but last summer the Vanuatu authorities went around with a portable generator and a TV and a brand-new UNESCO video about volcanoes, earthquakes, and tsunamis. They showed it in every village. The video described the Papua New Guinea disaster and warned, 'If you feel the ground shaking, or you see the water receding, run for high ground!' As it happened, the ground shaking in Vanuatu was not very strong, but they saw the water receding. There was a nearby hill, and they all ran up it. And stayed there. That's the big lesson—slumps can happen quite some time after the main shock, so we tell them to stay away for half an hour to an hour. It has happened in the past that a wave comes in and people run; then they return to look for loved ones or survey the damage, and they get hit by the second wave. Or the third wave. So for only three people to die in Bai Martele was amazing—spectacular! Of the people who died, two were very old, and the other one was high on kava, which is a local cognac. Of all the science we did, that was the best part. It really did save lives." A just-completed French bathymetric cruise has found a scarp off Bai Martele that has been interpreted as evidence for a landslide, but the jury is still out.

"This is a very exciting time," Synolakis says. "Tools developed over 40 years in diverse fields—classic long-wave theory, fluid mechanics, geophysics, soil science, oceanography, and seismology—are suddenly coming together. We have Fred Raichlen and his wave lab at Caltech to thank for this. He kept the field alive in the lean years of the '70s and '80s, when very few people were interested in tsunamis."

As you might have guessed by now, California is not immune to pocket tsunamis. We have as many faults offshore as onshore, and they're just

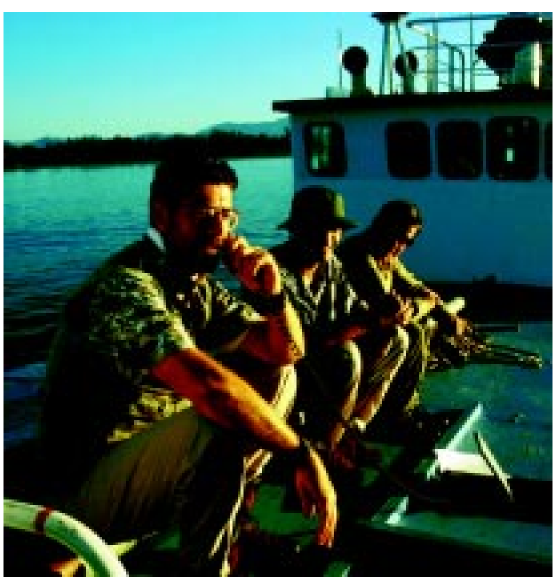


Above: At least three submarine landslides contributed to the arrowed region in this view of the seafloor south of Palos Verdes. The vertical scale is exaggerated tenfold. Unpublished composite image of high-resolution multibeam bathymetry courtesy of James V. Gardner, U.S. Geological Survey, Menlo Park, CA.

as active. Says Watts, "The geology and seafloor mapping off California is pretty complete in several key places, including San Pedro and Santa Monica Bays, largely due to the oil industry and the ports. The evidence would suggest there was a slump off Santa Barbara about 100 to 150 years ago—it's hard to be sure when—and another one 10 kilometers farther east about 300 years ago. Both of these are about an order of magnitude smaller than the one off Papua New Guinea, but they would be tsunamigenic because they occurred in much shallower water—at 100 meters' depth, rather than 1.5 kilometers. There are also slumps off Palos Verdes. This is a huge point: Northridge had thousands of documented landslides; Vanuatu had 2,000 documented landslides following the earthquake, so it's not unreasonable to expect a number to occur underwater as well."

In fact, Kuo-Fong Ma (PhD '93), postdoc Kenji Satake, now with the Geological Survey of Japan, and Kanamori found that the Loma Prieta earthquake of October 17, 1989, set off submarine landslides that created a small tsunami, 0.7 meters high, in Monterey Bay. The wave was recorded by tide gauges and, of all things, the video camera of a tourist who happened to pick that day to tape the sunset at Moss Landing.

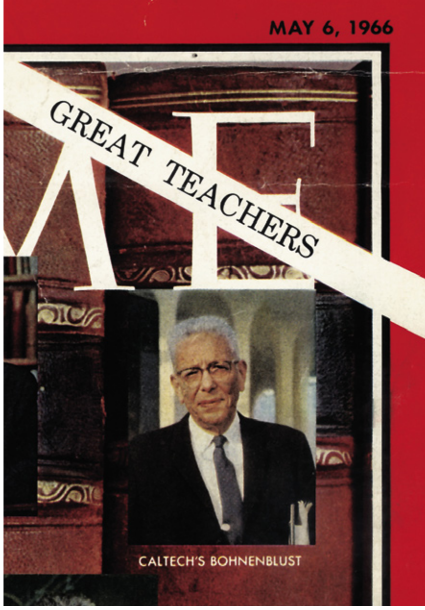
As *E&S* was going to press, the Governor's Office of Emergency Services of the State of California was releasing the first-ever set of tsunami inundation maps for the most populous locales along the California coast, analogous to the earthquake-hazard maps previously released. The maps, a joint effort with the Seismic Safety and State Lands Commissions, took two years to prepare. Synolakis, grad student José C. Borrero, and grad-student-turned-postdoc Utku Kanoglu did the modeling, which generated inundation scenarios for the San Diego, Los Angeles, and Santa Barbara areas, and from Half Moon Bay north to San Francisco. The flooding could be extensive, covering many low-lying areas and affecting port and harbor facilities, but there are other urban consequences. Paved surfaces don't dissipate wave energy, so roads become conduits. When the roads lead to underpasses, as they do in Santa Barbara where Highway 101 parallels the beach, you have a set of fire hoses aimed at downtown. And cars in beach-access parking lots become torpedoes. It's too late to unbuild along California's coastline, but knowing what's vulnerable and what will survive allows response teams to plan in advance how best to restore services and what kinds of relief supplies to bring in—you'll know where a railroad spur can be run over uneroded ground to bring in heavy cranes, for example, and you won't need so much diesel fuel if the tank farm is above the maximum run-up line. Issuing evacuation alerts is being considered as a means of saving lives—if the seismometers already affixed to offshore drilling platforms were tied into a computerized early-warning system, there could be about 10 minutes' notice of an incoming wave triggered by a slump in the Santa Barbara Channel. The best hope is to try to educate people not to hop in their cars and jam the freeways, but to simply run for high ground, including the upper floors of sturdy buildings. After all, the people on Vanuatu had even less warning, and if they could do the right thing, so can we. □



Left: In this day and age, you're never out of touch—Synolakis talks to colleagues in the National Oceanic and Atmospheric Administration in Seattle as José C. Borrero (center) and Okal look on. Right: The survey teams bade farewell at Madang International Airport. That's "Air New Guinea" in pidgin over the door.

Obituaries

Between last November and March, three former faculty members died who had been members of the Caltech community for a very long time. Vito Vanoni, who first came to Caltech as a freshman in 1922, and Victor Neher, who arrived for grad school in 1926, were both 95. "Boni" Bohnenblust was only 94; he joined the Caltech faculty comparatively late—in 1946.



Featured, with nine others, on a 1966 cover of *Time* magazine, Bohnenblust was described in the cover article as someone "perennially ecstatic about teaching basic mathematics to undergraduates."

H. Frederic Bohnenblust 1906 – 2000

H. Frederic Bohnenblust, professor of mathematics, emeritus, died March 30, 2000, in Santa Barbara.

A native of Neuchâtel, Switzerland, Bohnenblust received his bachelor's degree from the Federal Institute of Technology in Zurich in 1928 before coming to the United States as an exchange student. He earned his PhD from Princeton University in 1931 with a thesis that dealt with the application of abstract methods to Dirichlet series.

He remained on the Princeton faculty until 1945, but during World War II also did work for the National Defense Research Council in Washington, D.C.; studied the effects of bombing in England; and collaborated with Caltech's Theodore von Kármán and Don Clark on metallurgical problems. After a year on the faculty of Indiana University, he returned to Pasadena in 1946 as a full professor of mathematics at Caltech. He retired with emeritus status in 1974. Bohnenblust served as dean of graduate studies from 1956 to 1970 and was executive officer for mathematics from 1964 to 1966.

A strong advocate of mathematics education, Bohnenblust was featured in a 1966 cover article in *Time* magazine as one of the 10 outstanding university professors in the country. The article described him as remaining "perennially ecstatic about teaching basic mathematics to undergraduates. He handles a class of 100 students in almost Socratic fashion, keeping up a gentle, good-humored patter with students in the front rows and offering a soft 'Thank you' when they chuckle at his phrasing."

The *Time* article quoted Bohnenblust on his own style: "'Once you've understood that math is just straight thinking, just plain common sense,' he says, 'then anyone can do it.' He makes it even easier with his slow-paced, nontechnical language, constantly links math's logic to life. . . . 'I chose mathematics as my profession, not teaching,' he adds, 'but I love math and want to communicate its ideas—especially to the younger generation.'"

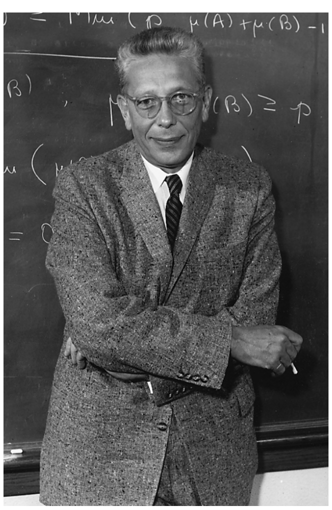
Professor of Mathematics Gary Lorden, BS '62, knew Bohnenblust both as an undergrad and as a colleague. "As a sophomore, I took a wonderful one-quarter course from him on game theory," said Lorden, "and I loved his elegant ways of explaining how mathematical theory is developed and applied. Better than anyone else, he showed us that mathematics is beautiful.

"At some point I had to turn in my own proof of some theorem—about a page long, the first one I ever wrote—and one day in his office he handed the paper back to me, giving me his big, twinkly smile and saying simply, 'I can read it!' That felt like the greatest compliment I'd ever received, and afterwards I began to seriously imagine becoming a mathematician."

In his "real" profession, Bohnenblust's specialty was functional analysis. When Bohnenblust retired in 1974, the late Robert Dilworth, then professor of mathematics and chairman of the faculty, described the subject as "just blossoming into a full-fledged research field when he began his mathematical career. Because of his enthusiasm and clear insight, his ideas had broad impact on the development of the field. . . . Appropriately, one of the basic results in the subject is the Bohnenblust-Sobczyk Theorem, which is still quoted frequently by workers in the field. (It would probably be quoted even more frequently except for a certain understandable pronunciation problem.)"

Bohnenblust also did work with game theory and was an early advocate of the use of computers in teaching and research. "Boni realized that here were tools that could overcome many of the deficiencies of blackboard and chalk," said Dilworth.

Bohnenblust was head of the mathematics department when Tom Apostol, now professor of mathematics, emeritus, arrived as an assistant professor in 1950. "He was personally responsible for transforming it from what was considered a 'service department' into a first-class research group," says Apostol.



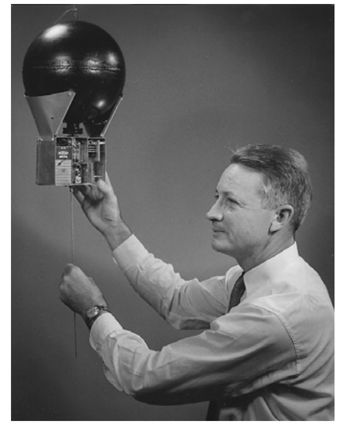
Apostol's initial experience teaching calculus convinced him that no textbook existed that was good enough for Caltech students. A committee organized by Bohnenblust considered for a year "what it is we want to teach our students" and how calculus should be taught. This led to Apostol's *Calculus*, published in 1961, which became the standard for courses all over the country. In the preface to the first edition, Apostol gave special thanks to Bohnenblust, "who first convinced me of the value of introducing integration via step functions and who supported the spirit and approach used throughout the book."

Apostol's "contact with Boni actually began years before I came to Caltech. As a graduate student in Berkeley, I studied the famous Bohnenblust Princeton Notes on Real Variables, which I still have in my library. I learned a lot from those notes."

Bohnenblust was also renowned for the Christmas punch he prepared every year for the mathematics party. It was "liberally spiced" with brandy and wine, and the dry ice that he ordered from chemistry made it into a spectacular show.

Friends and colleagues established the Bohnenblust Travel Grant to honor him when he retired. It still funds first-year graduate students whose mathematics projects require a journey abroad.

H. Victor Neher 1904 – 1999



H. Victor Neher, professor of physics, emeritus, died November 11, 1999, at the age of 95.

From graduate school onward, Neher's scientific career was spent at Caltech. Raised in California's San Joaquin Valley, where his father was a grain farmer, Neher attended grade school in a one-room schoolhouse. He enrolled in Pomona College, intending to study electrical engineering, but a physics professor invited him along to Caltech's Friday evening lecture demonstrations, where he first heard Robert A. Millikan speak (on magnetism, he remembered later) in the fall of 1922. After receiving his bachelor's degree from Pomona in 1926, Neher headed for graduate school in Pasadena.

As a grad student Neher worked under Earnest Watson on the scattering of high-energy electrons, earning his PhD in 1931. He stayed on as a research fellow to expand his thesis problem, but in 1932 Millikan asked him if he would like to work on cosmic rays. Neher ended up working on cosmic rays with Millikan, who had given them their name, for 20 years and continued this work for most of the rest of his academic career. He was named assistant professor in 1937, associate professor in 1940, and full professor of physics in 1944. Other members of Millikan's original cosmic-ray group included Bill Pickering (BS '32, PhD '36), later director of the Jet Propulsion Laboratory for 22 years and currently professor of electrical engineering, emeritus; and the late Carl Anderson (PhD '30), who discovered the positron, for which he won the Nobel Prize, while following the tracks of cosmic rays in his cloud chamber.

To investigate cosmic rays Neher invented electroscopes for ionization chambers, in which the rays ionize the gas inside, producing a charge that could be measured. Cosmic rays are very-high-energy charged particles—atomic nuclei, mostly hydrogen and helium, stripped of their electrons. They zip in from space (but also from the sun) and bombard Earth from all directions. Neher described them in a 1957 *E&S* article as "celestial bullets traveling at speeds very close to the speed of light."

Neher lugged his instruments to mountaintops, flew them in airplanes, launched them into space (on the Ranger and Mariner missions), and suspended them from balloons lofted to 135,000

Left: Neher in 1957 with one of his ionization chambers. Balloons carried these instruments to high altitudes to measure the intensity of cosmic rays.

feet above the Earth's surface. He estimated on his retirement in 1970 that he had launched about 400 balloons and had traveled the Earth from pole to pole (where cosmic rays are most intense) and in between. By studying cosmic particles, Neher and Millikan confirmed that Earth's magnetic center is 250 miles from its geological center. From his decades of data, Neher was able to plot a pattern of the density of cosmic-ray bombardment of Earth, a publication that remains a benchmark in cosmic-ray research.

Neher's ionization chambers and Pickering's Gieger counters often worked in tandem on the balloon flights. Pickering (who, as an undergrad in 1929, was taught physics by TA Neher) remembers a trip to India in 1939, during which they were to pick up the Millikans, who were already in Australia, en route. Hitler invaded Poland and World War II broke out before they set sail, but when they contacted Millikan about what to do, he told them, "Come on. Never mind the war." So they went. With most of the rest of their trip canceled, they made it to Calcutta on a series of ships via Singapore and Rangoon, launched several successful balloon experiments, and, deciding wisely to avoid their original route home through the Mediterranean, sailed back across the Pacific in 1940. It was "an interesting trip," says Pickering.

The bombing of Pearl Harbor found Neher, Pickering, and Millikan launching balloons in Mexico, where again, says Pickering, Millikan decided to ignore the war until they finished their work.

Eventually World War II did catch up with him, and Neher spent five years at MIT's Radiation Laboratory, under future Caltech president Lee DuBridge, designing and making microwave vacuum tubes. One of these, a K-band klystron, was known as the Neher tube. Last year Roy Gould (BS '49, PhD '56), the Ramo Professor of Engineering, Emeritus, traced its subsequent history and determined that the Neher tube was used in the first experimental maser, the predecessor of the laser. And Bill Bridges, the Braun Professor of Engineering, turned out to own a model of an early Neher tube, which he has donated to the Caltech Archives.

Returning to Caltech after the war, Neher was aware that high-energy physics was becoming the rage, but he had no interest in becoming involved in "big science." He preferred his independence. Caltech's involvement in cosmic-ray research consequently went down a different road after the 1962 arrival of Robbie Vogt, now Avery Distinguished Service Professor and professor of physics, with more advanced instrumentation from the University of Chicago. They were different generations in terms of technology. "Neher was heavily involved in my coming here," says Vogt. "He picked me up at the airport and was the first person I met from Caltech." But Neher made no attempt to draft him into Neher's own research group, instead allowing Vogt and his first postdoc, Ed Stone (see page 8), to go their own way. "He didn't make me miserable," says Vogt. "That was his generosity. He was a very, very generous, kind, and sensitive man, a man of immense integrity."

Ralph Miles, BS '55, PhD '63, was one of Neher's last graduate students and the last to do balloon flights, four of them with Neher in Greenland (where, in his late fifties, he was still hiking up glaciers). Neher had admired Millikan and wanted to finish his research, which he did. Thereafter, says Miles, Neher became more interested in teaching tools, constructing ingenious models to illustrate physical concepts. He conveyed his enthusiasm and skill at hands-on experimental physics to subsequent generations of students by building up the student labs—one of his great contributions to Caltech. He had a genuine affection for students, which was sensed and returned. As an adviser, says Miles, he was hands-off. "He didn't hover. He expected you to do independent research and didn't give you more advice than you asked for."

According to colleagues, Neher was among the last of the real experimental physicists who did their own work in the lab. He built his apparatus with his own hands. He was the "consummate experimentalist," says Vogt. "Vic had an intuitive understanding of making things work—a magic touch."

When he retired in 1970, he announced that he was not stepping down but starting the second phase of his life.

At the Indian Institute of Science physics department on February 2, 1940, Neher sits fourth from left next to Greta and Robert Millikan. Bill Pickering is fourth from right.

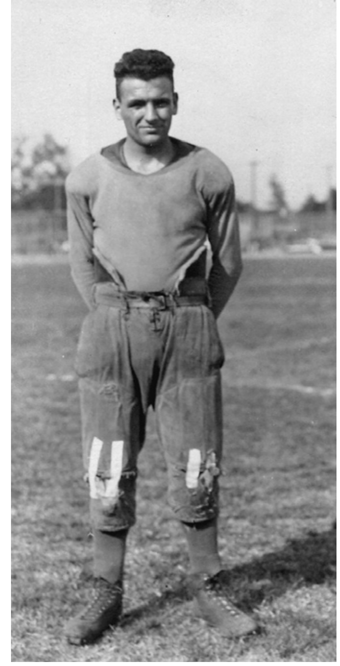
He and his wife, Sara, moved to redwood country near Watsonville, California, where they built their retirement home—with their own hands, of course—a house that survived just fine the 7.1 earthquake in 1989, whose epicenter was nearby. Neher also continued to do research, although not on cosmic rays. His last paper, published in 1993, was on "Effects of pressures inside Monterey pine trees." (He had also practiced close-to-home research in his Pasadena backyard, where, a friend remembers, he discovered through a few experiments in catching skunks, that if you dangle them by their tails, their own weight will keep them from squirting you.)

Neher never forgot his first Caltech experience—Millikan's 1922 demonstration lecture. He loved to explain to people how things worked and enjoyed putting on a spectacular show. In 1984, to celebrate the 20th anniversary of Beckman Auditorium, Neher returned to reprise Watson's famous liquid-air lecture, which had kicked off what is now known as the Earnest C. Watson Lecture Series, the descendant of those Friday evenings in Bridge Laboratory.

A SURF (Summer Undergraduate Research Fellowship) endowment has been established in Neher's name by an anonymous donor. His daughter (Neher is also survived by another daughter and three sons), Topsy Smalley, expressed her gratitude for so fitting a memorial: "The endowment is the perfect way of extending to others so much of what was central to Dad's own being. Dad fervently believed in the powers of education, in the worlds of possibilities that one-on-one faculty-student interactions could engender, and—most certainly—in the joys of finding things out."

On his Watsonville acres, Neher raised vegetables, chickens, rabbits, and goats. This photo was taken in 1977.

VITO A. VANONI 1904 – 1999



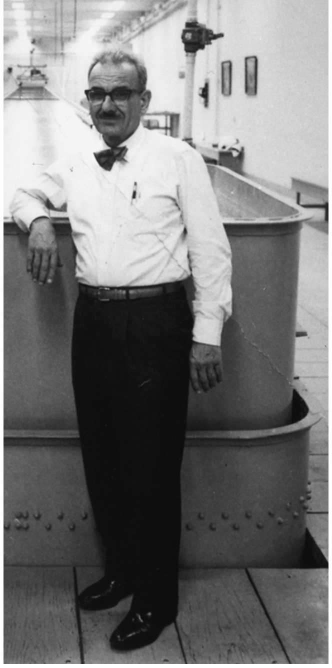
Vito A. Vanoni, professor of hydraulics, emeritus, died December 27, 1999, of congestive heart failure.

Although he "retired" with emeritus status in 1974, he continued to come to work into his nineties and was still a regular at the retirees' round table in the Athenaeum on Wednesdays. He had lunch there just 12 days before he died, according to Norman Brooks (PhD '54), the James Irvine Professor of Environmental and Civil Engineering, Emeritus, who planned the memorial service on February 5 for a most appropriate place. It was the first memorial luncheon at the Athenaeum that anyone could remember. "He would be pleased that we're having this luncheon party to celebrate his long, rich life," said Brooks.

Vanoni spent most of that long, rich life at Caltech. He graduated in 1926 with a BS in civil engineering. After five years of professional experience in structural steel design, he returned to Caltech for his MS in 1932 and PhD in 1940, also in civil engineering, and never really left. He was appointed assistant professor of hydraulics in 1942, associate professor in 1949, and professor in 1955, becoming a world authority on the mechanics of sediment transport by streams and rivers. He wrote a definitive and now classic manual, *Sedimentation Engineering*, published in 1975. Vanoni was elected to the National Academy of Engineering in 1977, was an honorary member of the American Society of Civil Engineers, and won two distinguished ASCE awards: the Hunter Rouse Hydraulic Engineering Lectureship and the Hans Albert Einstein Award.

Vanoni was born in 1904 near Somis in Ventura County, where his father, an Italian immigrant who worked on building Pasadena's Colorado Street Bridge to earn the money to bring over the rest of the family, had bought a hundred-acre farm. Vanoni Sr. was considered a "modern" California farmer, according to Vito's grand nephew, Andrew Vanoni, one who introduced such novelties as motor vehicles, flood control, and soil conservation and believed in what engineering could accomplish. He also knew the value of a good education and sent his son to the best engineering school around.

Andrew Vanoni recounted the story of one of his great uncle's early influences. At about the age of six, Vito had watched as "his father was



Far left: Vito Vanoni on Caltech's football field in the 1920s.
Left: at his flume in the basement of Keck Lab in 1965.

building the first phase of what I always called a ditch—a big, long cement ditch. It took my great-grandfather years to build it, eventually around the entire farm perimeter. And it's still there today, doing what it's supposed to do—sitting there in dry weather and becoming a landsaver when it rains." Andrew had only recently discovered, after his great uncle died, that this was not a ditch but actually an "open channel flume."

Vito Vanoni grew up to design open channel flumes in which he carried out his meticulous experimental research. "Vito was the ultimate experimenter," said Brooks. "For his PhD research, he did the first and most definitive and careful experiments on sediment carried in suspension in rivers. " It's still regarded as one of the classic contributions to the field. Vanoni designed and built a 60-foot-long, 3-foot-wide flume for Caltech's Sedimentation Laboratory, which was operated in cooperation with the U.S. Soil Conservation Service, and which he supervised from 1935 to 1947. The temporary building stood just west of the present Chandler Dining Hall. This research moved into the W. M. Keck Laboratories in 1960.

Fredric Raichlen, professor of civil engineering and mechanical engineering, who arrived at Caltech as an assistant professor in 1962, described Vanoni's early work in coastal engineering. During the war years Vanoni did defense-related research, primarily in the investigation and control of wave action in harbors, using hydraulic models (of Long Beach Harbor, among others) on campus and later in a large off-campus wave basin in Azusa. His work in coastal engineering and hydraulic structures continued in the '60s and '70s, when Raichlen worked with him on a number of projects. "He demonstrated to me the importance of observations in an experiment, rather than just going and conducting the experiment. I remember him sprinkling fine coal in the model to trace currents and then pointing out to me the effect of intersecting waves in the lee of the island on these currents."

Brooks noted that "as a thesis adviser, he showed me that careful observations trumped theories if they disagree. He turned me from being a young, idealistic theorist into a careful observer and pragmatist. Once, when I was doing some experiments, sand dunes appeared in the flume I was using, when I thought the sand bed should stay flat. They weren't in my calculations, and I consulted with Vito as to how I could get rid of them so I could check my theories. And he said, 'Young man, that's the way it is, so that's what you should study.' So I did."

Vanoni was not an advocate of computer modeling in sediment engineering, according to Hasan Nouri, president of Rivertech, Inc., who began consulting with him in 1975. He related the tale of a colleague who came to Vanoni with his computer model, claiming that it predicted exactly what the survey showed. "Professor Vanoni looked at him and said, 'The science of sedimentation engineering is not that precise. You must have made a mistake somewhere!'"

All of the speakers mentioned the extraordinary hospitality and friendship of the Vanonis (his wife of 61 years, Edith, died in 1995). Vanoni tended a large garden (or a small farm) in what he called his "back 40"; they hosted an annual Halloween party and allowed all the children to take home as big a pumpkin as they could carry. "They were very affectionate people," said John List, PhD '65, professor of environmental engineering science, emeritus, "and they really gave genuine attention to young people, which was impressive in a senior faculty member at Caltech. Eating Vito and Edith's crop of the season in their wonderful garden and listening to Edith's sometimes bizarre stories of their travels is something that we'll carry with us forever."

Sally Daily, whose late husband, James Daily (MS '37, PhD '45), was an early colleague of Vanoni's ("I'm sure Norman asked me to say something because there aren't too many people around who knew Vito for more than 60 years") spoke of some of their travels together. "Scores of friends all over the world saw him as someone who was truly interested in people for themselves and who had a real gift for friendship," said Daily. Other speakers noted his energy, liveliness, and enthusiasm in his work as well as outside it.

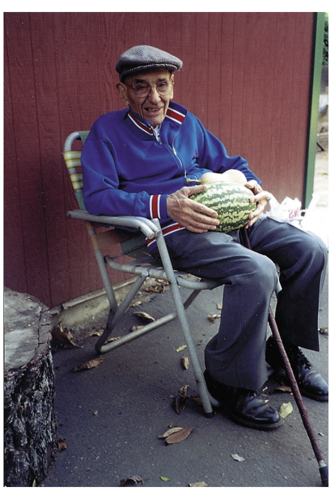
Both Brooks and Li-San Hwang (PhD '65) were among Vanoni's doctoral students. Hwang appreciated Vanoni's rigorous training not only in sediment engineering but also in other skills. "He was my English professor, in a sense, correcting my English grammar," said Hwang, "and he also taught me the things I needed to succeed in business, in the real world." Hwang, who is now president and CEO of Tetratech, Inc., announced that he was establishing an undergraduate scholarship at Caltech in Vanoni's honor.

Brooks, who was closely associated with Vanoni for 49 years, noted that "I've been through several ages of man with him, you might say. First the four years as my PhD adviser, then the 20 years as a faculty colleague, and finally 25 years as an emeritus colleague, the last four of which I've also been emeritus."

Raichlen remembered "his quandary when he had to retire. We'd sit at the round table, and he would turn to everyone who was either retired or going to retire and would ask them: 'What are you going to *do* when you retire?' And he was never happy with any answer he got." He tried it for a while, but "he would come in a little earlier, and a little earlier, until finally in his late eighties or maybe when he was 90, he would come in about 9 and leave at 3 or 4, apologizing for leaving so early."

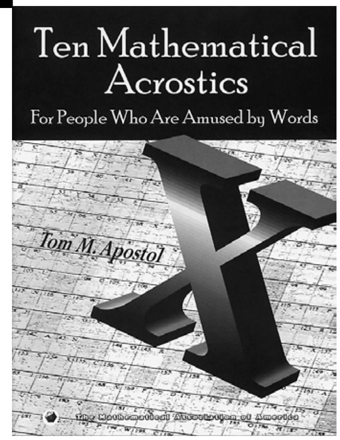
"That is what I call young old age," said Brooks, "which lasts until your transition to old old age. Vito made young old age last for about 20 years, going to the lab almost daily, writing papers, doing consulting work. He greatly enjoyed consulting with the Corps of Engineers after the Mount St. Helens eruption in the early 1980s about what to do with all that extra sediment." In Vanoni's old old age, Brooks would take him on short excursions and continued to bring him into the lab. "He'd go with his cane but we'd also bring a chair. When we'd get to the flume, I'd sit him down because if he got too interested he might not pay attention and lose his balance."

The Vanonis had no children, but List noted that Vito had left a "legacy in his academic children and grandchildren and great-grandchildren all over the world. . . . Vito and Edith passed through life without a great deal of drama and fanfare and pomposity, and left us in much the same way," he said. "We'll do well to remember the example they set. Good memories will endure." □



Vanoni with one of the products of his legendary garden in the fall of 1999.

Books



Back in the early '70s, Double-Crostic fan Tom Apostol (also professor of mathematics, emeritus) constructed such a puzzle for his colleagues at the annual West Coast Number Theory Conference; it was unique in that all the words and all the clues, as well as the ultimate solution, related in some way to mathematics or mathematicians (sample clues.: "Euler's function"; "two of the creators of functional analysis").

Apostol's clever exercise was an instant hit, and he duly produced nine more for a decade's worth of conferences. All have now been collected in a small booklet published by the Mathematical Association of America—*Ten Mathematical Acrostics: For People Who Are Amused by Words*.

Although the cover blurb claims that "most of these puzzles can be (and have been) solved by people who know little or no mathematics but have a good vocabulary," an excellent memory of your college math courses and a handy volume on the history of mathematics will help. Even if your vocabulary can cope with "type of equation," it might have a bit of trouble with "two over the square root of pi times the integral from 0 to W of exp(—t^2) *dt*" And though you might consider yourself a person "amused by words," if you don't know much about math history, you might not be chuckling to yourself as you tussle with "early Japanese form of integral calculus" or "Irish mathematician (1826–1883) who studied quadratic forms."

As a further hint, the first letters of the answers to the clues spell out the author and title of the work containing the passage that constitutes the solution. So if you're really familiar with, say, Hardy's *Integration of Functions*, it's a snap. Of course, then there's the German passage, just to make it a little bit more difficult; at least its clues are in English.

But Apostol, in his introduction, cautions the fainthearted not to be intimidated at first glance. Because the nature of acrostics is a back-and-forth process, one answer allows you to intuit quite a few missing letters and, thus, words. The solutions, at least, do consist almost entirely of common, recognizable English words. Apostol claims, "If you can guess five or six of the words correctly, you should have enough information to complete the solution." Except maybe that German one . . .

So, for example, if you know that "facts or figures" are "DATA" and that "where QED appears" is "ENDOFTHEPROOF," then you can put the two T's where they belong in a nine-letter word in the solution. By the time you get that "a kind of product" could be "CROSS," and what "often accompanies jays" is "EYESANDKAYS," you have a C and a K for _TT_CK_ _ _, and can reasonably assume that the word is "ATTACKING." Then you can fill in those extra letters (including three vowels) back under the clues, where the two A's may help jog your memory to come up with "HADAMARD" as one of those "creators of functional analysis." Now you've got several more letters—a bunch of critical consonants—to fill in where *they* belong in the solution. And so on. Apostol says, "Once you have filled in just a few letters in the diagram, you will be amazed to see words and phrases begin to take shape." Well, make that *quite* a few letters.

Anyone up for the challenge can order Apostol's acrostics from the Caltech Bookstore for $9.95. Also available (for $39.95), for those who prefer something less than total immersion, is *Patras Diary*, by Jane Apostol, Tom's wife: an entertaining account of a semester in 1978 spent teaching mathematics in Greece—leavened with accounts of travel and delicious meals among Tom's Greek relations. Add $3 for postage and handling ($4 if you order both). □

Caltech Bookstore, 1-51,
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phone: 626-395-6161;
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President David Baltimore accepts the 1999 National Medal of Science from President Clinton at a White House ceremony on March 14. Baltimore, one of 12 honorees, was cited "for far-reaching, fundamental discoveries that dramatically altered fields of study in virology, molecular biology and immunology, for excellence in building scientific institutions, and in fostering communication between scientists and the general public."

Richard Murray to Chair EAS Division

Associate Professor of Mechanical Engineering Richard M. Murray (BS '85) has been named chair of the Division of Engineering and Applied Science, replacing John Seinfeld, Nohl Professor and professor of chemical engineering, who is returning to full-time faculty and research duties after a decade as chair. The appointment becomes effective June 1.

Murray has been a faculty member since 1991. His research interests include nonlinear control of mechanical systems with applications to aerospace vehicles and robotic locomotion, active control of fluids with applications to propulsion systems, and nonlinear dynamical systems theory. He earned his bachelor's degree with honors in electrical engineering from Caltech in 1985, and his master's and PhD in electrical engineering from the University of California at Berkeley in 1988 and 1991, respectively. Before joining the Caltech faculty, he was a visiting lecturer at Berkeley, where he taught graduate-level classes in robotics.

In addition to his academic work, Murray has worked as an engineer at JPL, where he worked on the Galileo spacecraft, now orbiting Jupiter. In 1998–99, he was director of mechatronic systems at the United Technologies Research Center, where he managed an embedded systems and controls technology department consisting of 80 engineers, technicians, and staff.

Honors and Awards

Frances Arnold, Dickinson Professor of Chemical Engineering and Biochemistry, and *Douglas Rees*, professor of chemistry and investigator, Howard Hughes Medical Institute, have been elected to the National Academy of Sciences. Arnold was also elected to the National Academy of Engineering. Such election is one of the highest honors that can be accorded a U.S. scientist or engineer.

Jacqueline Barton, Hanisch Memorial Professor and professor of chemistry; *Alice Huang*, senior councilor for external relations and faculty associate in biology; *John Seinfeld*, Nohl Professor and professor of chemical engineering; and *David Stevenson*, Van Osdol Professor of Planetary Science, have been elected Fellows of the American Association for the Advancement of Science, an elevation granted some members "because of their efforts toward advancing science or fostering applications that are deemed scientifically or socially distinguished."

Donald Cohen, Powell Professor of Applied Mathematics, will receive Caltech's Richard P. Feynman Prize for Excellence in Teaching.

The Economic History

Network has selected the book *Institutional Change and American Economic Growth*, by Harkness Professor of Social Science *Lance Davis* and Douglass North, as one of the 12 most significant works in economic history published during the 20th century.

Peter Dervan, Bren Professor of Chemistry, received the 1999 Richard C. Tolman Medal of the Southern California Section of the American Chemical Society, given annually "in recognition of outstanding contributions to chemistry in Southern California."

Associate Professor of Economics *Jeffrey Dubin* has been awarded a 2000 Haynes Foundation Faculty Fellowship to assess the economic impact of the San Fernando Valley's seceding from the city of Los Angeles. The foundation makes grants for study and research in the social sciences, with emphasis on policy issues of the greater L.A. region.

Assistant Professor of Economics *Caroline Fohlin* has been selected to write the ninth annual Sanwa Monograph on International Economics and Financial Markets by the Stern School of Business, New York University.

David Goodstein, professor of physics and applied physics and Gilloon Distinguished Teaching and Service Professor and vice provost, will receive Sigma Xi's 2000 John P. McGovern Science and Society Award.

Harry Gray, Beckman Professor of Chemistry and director of the Beckman Institute, has been elected a Foreign Member of Great Britain's Royal Society for "seminal contributions to virtually every area of modern inorganic chemistry."

Robert Grubbs, Atkins Professor of Chemistry, will be awarded the Herman F. Mark Polymer Chemistry Award from the Division of Polymer Chemistry of the American Chemical Society for his outstanding achievements in research and leadership in polymer science.

Assistant Professor of Physics *Fiona Harrison* has been selected to receive a Presidential Early Career Award for Scientists and Engineers.

Professor of Astronomy and Planetary Science and Executive Officer for Astronomy *Shrinivas Kulkarni* has been invited by MIT's physics department to give the David Harris Lectures for the year 2000.

Assistant Professor of Physics *Hideo Mabuchi* (PhD '98) has been chosen as an Office of Naval Research Young Investigator. He was one of 26 investigators selected from 178 applicants.

Frank Marble (AE '47, PhD '48), Hayman Professor of Mechanical Engineering and professor of jet propulsion, emeritus, will be given the 1999 Daniel Guggenheim Medal from the United Engineering Foundation "for major fundamental theoretical and experimental contributions to the fields of internal aerodynamics, combustion, and propulsion… and educating generations of leaders in industry and academia."

Professor of Biology and Executive Officer for Biology *Elliott Meyerowitz* has received the Lounsbery Award from the National Academy of Sciences.

Dianne Newman, Luce Assistant Professor of Geobiology and assistant professor of environmental engineering science, and Assistant Professor of Computer Science and Computation and Neural Systems *Erik Winfree* (PhD '98) have been selected by MIT's *Technology Review* for its list of "100 young innovators who exemplify the spirit of innovation in science, technology, business and the arts."

Associate Professor of Applied Physics *Stephen Quake* has been selected as a 1999 Packard Fellow for Science and Engineering.

Alexander Soshnikov, Taussky-Todd Instructor in Mathematics, has received the Moscow Mathematical Association's 1999 Young Mathematician's Prize, which is given to a Russian mathematician under 30 for outstanding work.

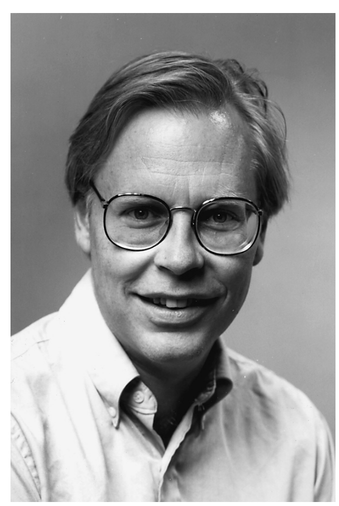
Professor of Electrical Engineering *P. P. Vaidyanathan* has been awarded a Golden Jubilee Medal by the Circuits and Systems Society of the Institute of Electrical and Electronics Engineers.

Alexander Varshavsky, Smits Professor of Cell Biology, and Avram Hershko of the Technion–Israel Institute of Technology will share the Alfred P. Sloan, Jr., Prize, awarded by the General Motors Cancer Research Foundation, "for the discovery of the ubiquitin system for protein degradation and the crucial functions of this system in cellular regulation."

Ahmed Zewail, Nobel laureate, Pauling Professor of Chemical Physics and professor of physics, has been given the Faye Robiner Award by Ross University, New York, and has been elected a Foreign Member of The Royal Danish Academy of Sciences and Letters.

KIEWIET NEW DEAN OF GRADUATE STUDIES

In other administrative news, Professor of Political Science D. Roderick Kiewiet has agreed to assume the duties of the dean of graduate studies, starting July 1, 2000. Kiewiet is not unfamiliar with the territory, having previously been dean of students from 1992 to 1996. He replaces Professor of Geology and Planetary Science Arden Albee, who is stepping down after 16 years of service to devote his full attention to Mars.



David Stevenson (left) and George Van Osdol at Seminar Day in 1996.

How to Have Your Cake...And Eat It Too

After graduating from Caltech in 1934 with a BS in electrical engineering, George Van Osdol, Sr., spent a couple of years at U.S. Electrical Motors in Los Angeles before embarking on a 30-year career with Pacific Bell in L.A. and Pasadena, where he designed and engineered interoffice communication facilities. Van Osdol's career was interrupted by several years in the naval reserve during World War II. He was first stationed at the Boston Naval Yard, then in San Francisco, and finally on Bikini Island, where he was in charge of electronic maintenance for the atomic-bomb tests known as the "Crossroads Project."

Since his student days, Van Osdol has maintained an appreciation for the Institute and the important scientific work emanating from the campus. He has attended many Watson Lectures over the years, and eagerly looks forward to Seminar Day every May.

George had long contemplated including a bequest to Caltech in his will. After his retirement from Pac Bell in 1977, he began to investigate the idea of making a gift of his home while retaining a life estate. "I was trying to find the catch. I thought there must be a 'hook' in there someplace," he mused. It seemed too good to be true that he could deed his home to charity, receive a charitable deduction on his current income tax, and still retain the right to live in the residence for the rest of his life; but that is precisely what this plan allows. In 1990, with the assistance of the staff in Gift and Estate Planning, he arranged to do just that.

Van Osdol then began exploring the possibility of funding an endowed professorship. He initially intended to fund the professorship in his will, but decided that it would be more rewarding to fund the chair while he was living so that he would have an opportunity to know the person(s) who would benefit from his gift. In addition, substantial income-tax benefits would be realized by making a charitable contribution during his lifetime. So, in 1993, he began the gifts needed to fund a professorship, one made even more valuable by not being restricted to a particular division. In keeping with his generous nature, the Van Osdol Professorship is awarded wherever the president or provost deems the need to be greatest.

In 1996, David Stevenson was appointed the first George Van Osdol Professor of Planetary Science. Shortly thereafter, Van Osdol and Stevenson met at a luncheon. Since then, they have continued to correspond periodically and have made lunch at the Athenaeum an annual event. Stevenson, a native of New Zealand, joined the Caltech faculty in 1980. His research concerns the origin, evolution, and structure of planets. The funds received from this professorship are extremely important to his work, as they allow him great flexibility in their use.

Having already made two extraordinarily generous gifts to the Institute, in 1999 Van Osdol set up charitable remainder unitrusts for his children and a close family friend. He will receive tax deductions; the trust beneficiaries will receive quarterly distributions from their respective trusts as long as they live; and the remainders will go to Caltech at the ends of the beneficiaries' lives to provide additional endowment for the Van Osdol Professorship.

Obviously, Van Osdol has done his homework well and has figured out that "planned giving" is just that. Good planning offers significant benefits to him, to his heirs, and to Caltech. The money earned and saved during his lifetime will continue on as his legacy, making an important difference in the scientific world for a long time to come.

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