California
Institute of
Technology

E&S
ENGINEERING AND SCIENCE

Volume LXII,
Number 3,
1999

IN THIS ISSUE

Jonathan Miller's long career as a theater and opera director includes Mozart's *Le Nozze di Figaro* (Act I shown here) for New York's Metropolitan Opera last year. Miller started out, however, as a neurologist. In an article beginning on page 28, he discusses how patients with damaged brains resemble actors performing, how an invisible reflective surface is a metaphor for the mind, and how an opera director uses Mozart's "genetic" instructions to create something intriguing for a modern audience. (Photo courtesy of the Metropolitan Opera; © Beth Bergman)

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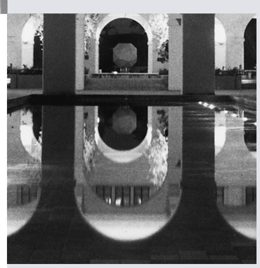

On the cover: (from left) Andreas Piepke, senior research fellow in physics; Herb Henrikson (BS '53), member of the professional staff; and the Arizona Public Service Company's Rodney Wilferd stand in the excavation that will house the Palo Verde Neutrino Detector. The detector is on the grounds of the Palo Verde Nuclear Generating Station, a prolific neutrino source. For a peek at what the detector is seeing, look at the story on page 12.

Engineering & Science (ISSN 0013-7812) is published quarterly at the California Institute of Technology, 1200 East California Boulevard, Pasadena, CA 91125. Annual subscription $10.00 domestic, $20.00 foreign air mail; single copies $3.00. Send subscriptions to Caltech 1-71, Pasadena, CA 91125. Third class postage paid at Pasadena, CA. Published by Caltech and the Alumni Association. Telephone: 626-395-3630.

PICTURE CREDITS: Inside front cover, 33–34 — Winnie Klotz/Metropolitan Opera; 3, 6, 7, 14 — Doug Smith; 4 — Douglas Hill Photography; 5 — Bill McMillan; 7, 9, 23, 25, 28, 30, 40 — Bob Paz; 10, 11 — JPL; 10 — David A. Paige, Ashwin Vasavada; 12 — Arizona Public Service Company; 17 — Joachim Wolf; 18 — Andreas Piepke; 29 — Ken Howard; 36 — Christus Rex and Redemptor Mundi, L.A. County Museum of Art; 39 — Terry Cole

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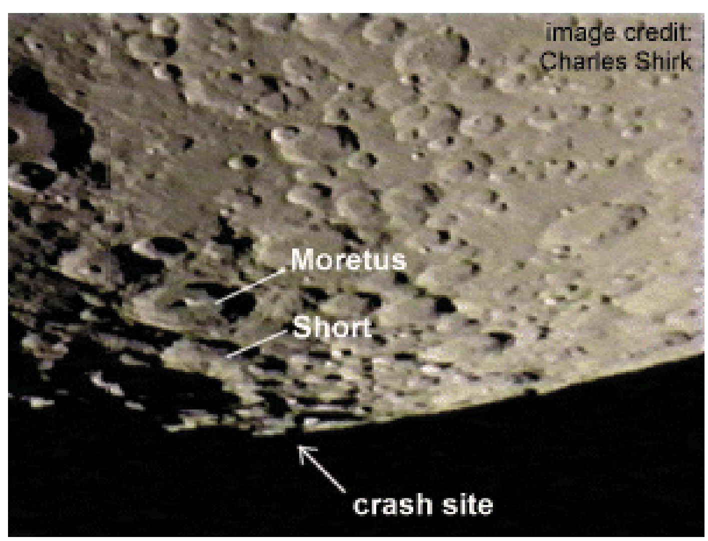
Digital Critters

A team of researchers from Caltech and elsewhere have created "digital organisms"—computer programs that self-replicate, mutate, and adapt by a process analogous to natural selection, and whose response to mutations closely resembles the way real organisms evolve. Chris Adami, senior research fellow in computation and neural systems, and colleagues found that the overall effect of many mutations can actually result in a "better," more fit organism than one would predict from multiplying together the effect of the individual mutations—a result that matches experiments with real bacteria, fungi, and fruit flies. Adami says this is particularly exciting because it shows that digital organisms can be used by researchers to answer important biological questions—"The advantages are that it's very simple, and that it abstracts the system as much as possible. Living systems on Earth are very complex after four billion years of evolution, so it's very difficult to ask the most fundamental questions of them. For example, we can reconstruct a genetic tree, then change the origin of the tree slightly and rerun the entire tape of evolutionary history. If we change just one molecule way back, we discovered it can change everything."

The work has implications for searches for life beyond Earth, because no one really knows exactly how life got started and how it proceeded to grow in complexity. Therefore, no one really knows all the ground rules of life. "If we go somewhere else, are we going to find life that is similar or totally different? If it's similar but unrelated, then life is perhaps constrained narrowly. But if it's totally different, then maybe life is constrained very loosely."

The digital organisms are based on principles that are known about life here and assumed likely to be true of life elsewhere: living systems replicate, they conserve information, and they have dynamic properties that differ from other living systems and allow adaptations. By building a digital petri dish—an ecosystem, really—in which the programs "live," the researchers can allow the programs to fill a niche, interact with each other, mutate and adapt to local conditions, die out, provide opportunities for other organisms to fill the niche—all the things that organisms on Earth really do, but over many eons.

Adami hopes the work, which appeared in the August 12 issue of *Nature*, will help settle the debate about whether running experiments with digital organisms in a computer is really biology, as biologists understand it. It doesn't hurt that his collaborator is a respected biologist with many years of outstanding accomplishments using real petri dishes. "Richard Lenski is the world's expert at doing experimental evolution with *E. coli*," Adami says.



On July 31, 1999, the late Eugene Shoemaker (BS '47, MS '48) became the first human to be buried on the moon (or on any other nonterrestrial object, for that matter) when the Lunar Prospector, which carried a lipstick-sized vial of his ashes, crashed into a crater near the lunar south pole. The spacecraft, which had been orbiting the moon since January 11, 1998, was searching for signs that water ice might lurk in the moon's subsurface. This kamikaze finale was the culmination of that effort. It has been hypothesized that polar craters might hold frozen lakes, their water protected from evaporation by the everlasting night in which they lie, and it was hoped that the spacecraft's impact would send aloft a plume of ice particles that would be detectable from Earth. (No plume was visible, but the astronomers are still analyzing their data.) Shoemaker, one of the Caltech geologists who trained the Apollo astronauts to be scientists as well as fliers, had a lifelong dream to go to the moon himself.

"This paper is the first result of the collaboration, in which we repeated an experiment he has already done with *E. coli*. So I think this is the first time we have convinced biologists that artificial life is not just a pipe dream, but is answering some fundamental questions about biology."

Lenski is with the Center for Microbial Ecology at Michigan State University. The other collaborators are Charles Ofria (PhD '99), who is now a postdoc in Lenski's lab; and Travis C. Collier (BS '97) of the UCLA Deparment of Organismic Biology, Ecology and Evolution. □—*RT*

Number One

Caltech came out on top in this year's ranking of national universities by *U. S. News and World Report*, followed, in order, by Harvard, MIT, Princeton, Yale, and Stanford. The magazine bases its rankings on academic reputation (25 percent), graduation and retention rates (20 percent), faculty resources (20 pecent), student selectivity (15 percent), financial resources (spending per student; 10 percent), alumni giving (5 percent), and graduation-rate performance (the difference between actual and predicted graduation rates; 5 percent).

Although Caltech has always placed in the top 10 (last year it was ninth), it was a change in the magazine's statistical procedures, which formerly had flattened out the actual differences but now weighted them, that vaulted Caltech into first place. *U.S. News* admitted that these changes "boosted the rankings of a number of universities with strong science and engineering programs." The magazine pointed out that "[w]ith few students and many pricey scientific facilities, Caltech's average per-student spending is a whopping $192,000." But the Institute also placed first in faculty resources, freshmen in the top 10 percent of their high school classes (100 percent), SAT scores, and student/faculty ratio (3 to 1).

According to an accompanying article in the August 23 issue of the magazine: "At Caltech, would-be engineers and scientists can have it all: plentiful opportunities to learn at the feet of award-winning professors . . . and the sense of community that one finds at small schools." Amidst all the praise, however, the article did note that the racial and gender balance left something to be desired, not to mention the social life, as the *Princeton Review* observed in ranking Caltech among the worst party schools.

In yet another ranking, the September issue of *Kiplinger's Personal Finance Magazine* rated Caltech number 2 among the "Top 100 Values in Private Colleges." □

In preparation for its voyage to Chile, the Cosmic Background Imager—a 34-ton array of 13 one-meter radio telescopes—was hoisted onto an intermodal cargo platform called a "flat rack" (upper left) on July 8, and battened down against the elements by principal investigator Tony Readhead (upper right). The crane returned on August 2 to lift the now-crated CBI onto a flatbed truck for the trip to Long Beach Harbor. The CBI and its 10 shipping containers of support equipment arrived in Antofagasta, Chile on August 22, and reached the observatory site high in the Andes on the 28th. The telescope is now in its dome, and the shipping containers, which will double as offices, have been unpacked. The astronomers are now reinstalling the telescope's delicate components, and hope to soon begin looking for the seeds of the very first galaxies.

The Athenaeum dining-room ceiling was restored this summer to its former splendor. Originally designed by John Smeraldi in the Italian Renaissance style popular when the Ath was built, the ceiling had suffered over nearly 70 years of smoke and grime. Under the supervision of Tony Heinsbergen, son of Smeraldi's biggest local competitor, it was cleaned, in some places repainted, and varnished. Perhaps the most satisfying step of the restoration was the removal of acoustic tile (glued on during a '60s renovation to dampen the clatter of silverware) to reveal the original teal-blue panels beneath, bordered by patterned red and gold moldings. Romy Wyllie, the Athenaeum's interior designer, instigated the restoration project. Her book on Caltech's architecture will appear in December.

Lost in Space?

Long, long ago in a solar system not at all far away, five to ten Earth-like planets could have occupied Jupiter-crossing orbits. Warmed in the blanket of molecular hydrogen they accreted when the solar system formed, these planets could today be harboring life somewhere in interstellar space, said David Stevenson, Van Osdol Professor of Planetary Science, in a paper in the July 1 issue of *Nature*.

Called "interstellar planets" because they no longer orbit their parent star but instead drift through the void between the stars, such objects have never been directly observed, or even proved to exist. But based on what scientists know about the way matter should fall together to create a solar system, such planets could definitely have been formed. Then, over several million years, one of two things would have happened to them: either they slammed into Jupiter and were swallowed up, or they came close enough to Jupiter to be catapulted by its gravity completely out of the solar system, never to return.

Because these bodies formed when the solar system was permeated with hydrogen gas, they would have retained a dense atmosphere of hydrogen. Without sunlight, the natural radioactivity inside an Earth-like planet would only be sufficient to raise the radiating temperature of the body to 30 degrees above absolute zero (that's about minus 400 Fahrenheit), but a dense hydrogen atmosphere would trap that heat—just like the greenhouse effect on Earth, but more so. Over the eons, the planet's surface could attain Earth-like surface temperatures, allowing oceans of liquid water to form. (The dense atmosphere would also create a surface pressure similar to that at the bottom of Earth's oceans.) For this to happen, the interstellar planet would probably need to be at least half Earth's mass.

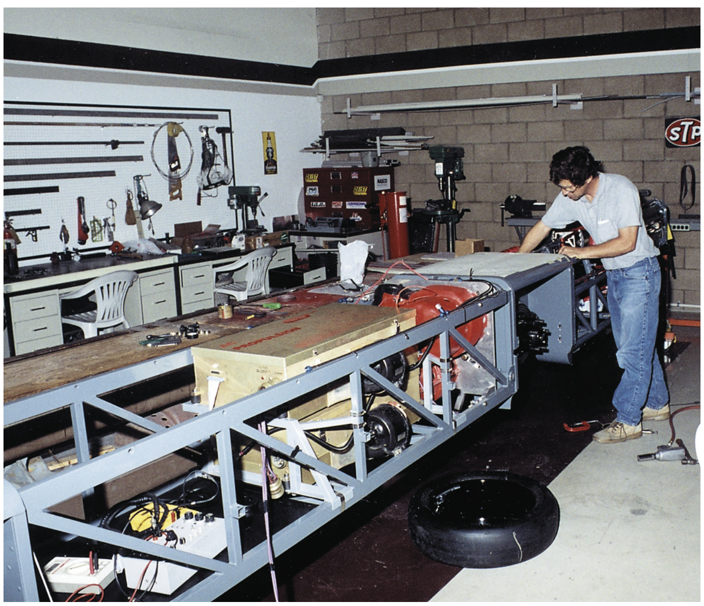
It is not known whether geothermal heat alone is sufficient to allow life to originate, and the amount of energy would be small compared to sunlight, suggesting that the amount of biological activity would also be small. But the existence of life in

In a tangentially related story, grad student Adam Burgasser has found four brown dwarves—stellar wannabes bigger than Jupiter but too small to ignite their hydrogen-fusion reactors—while sorting through data from the Two-Micron All Sky Survey, for which Caltech's Infrared Processing and Analysis Center (IPAC) is doing the data reduction. Assistant Professor of Planetary Astronomy Michael Brown then trained the 10-meter Keck Telescope on Burgasser's sets of coordinates (in the Big Dipper, Leo, Virgo, and Corvus the crow) and found the spectral signature of methane, which dissociates at temperatures above 1200 kelvins—only twice as hot as your oven when you're trying to cook a roast in a hurry. "I was specifically looking for brown dwarves in the latter stages of their evolution," says Burgasser. "And that's what these have to be—no other substellar object could cool to temperatures where methane can form." Brown dwarves are so dim that only about a dozen have been discovered so far, and methane-rich brown dwarves are the rarest of the rare—grad student Ben Oppenheimer (PhD '99) and astronomy professor Shri Kulkarni found the first one in 1995. Until now, it was the only one known. This new batch, plus one discovered by the Sloan Digital Sky Survey, will help theorists flesh out the models of a brown dwarf's life cycle, giving us a better understanding of these odd creatures that are neither planet nor star.

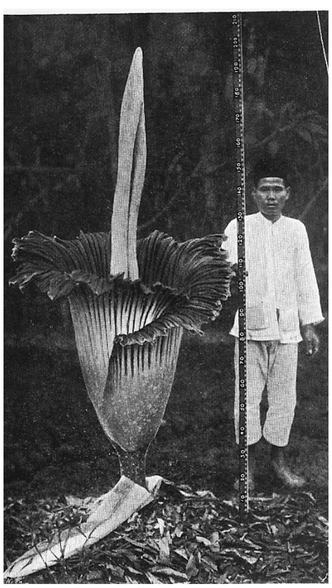
But although very few of them have been found so far, they are probably as common as the stars we see. Davy Kirkpatrick, an IPAC senior staff scientist who is looking for slightly hotter brown dwarves, estimates that the new crop is only about 30 light years away—right in our own back yard, in galactic terms. The fact that we can just barely make them out at such close range implies that the Milky Way, like L.A., is full of wandering stars that never made it.

such an environment would be of great interest, even if the mass of living matter were small. The heat energy, and especially variations in temperature, could potentially allow life to get going, Stevenson says. "I'm not saying that these objects have life, but everyone agrees that life requires disequilibrium. So there has to be a way to get free energy, because that's what drives biochemical processes. These objects could have weather, variations in clouds, oceans… even lightning." If life exists on such objects, how complex that life could be is an open question, he says. "I don't think anyone knows what is required to drive biological evolution from simple to very complex systems."

These interstellar wanderers could be a common by-product of star formation, but even if such a planet formed in our own solar system and is still hanging around the neighborhood, it would be very difficult to see with present technology. Although these bodies may have warm surfaces, not much heat would escape into space and they would appear dark and cold to us—at best, as very weak emitters of long-wavelength infrared radiation, far below current detection limits. The best bet for demonstrating that interstellar planets exist would be a programmed search for occultations, Stevenson says. The object might occasionally pass through the line of sight from Earth to a star, and if instruments were watching, the starlight might dim or even flicker out for a moment. Such programs have already been advocated to look for planets in orbit around other stars. Looking for interstellar planets would be much harder, he says, but it could be very rewarding. "All I'm saying is that, among the places you might want to consider for sustainable life, you might eventually want to look at these objects. They could be the most common location for life in the universe." □—*RT*



Left: Alan Cocconni (BS '80) checks some connections in the cockpit wiring of the *White Lightning* (below), an electric vehicle that set a land-speed record of 239.533 miles per hour at the Bonneville Salt Flats on August 20. The car was powered by 6,210 rechargeable nickel-cadmium "sub-C" batteries—a lighter-weight variant of the kind sold in hobby stores for radio-controlled models. "They discharge fully in 90 seconds—the fastest battery on the market at the time" says Cocconni, whose company, AC Propulsion, provided the power inverters (gold boxes) and 200-horsepower electric AC motors (red). "It's a standard drive system we've been selling to electric-vehicle builders and researchers for eight years," he says. "But not with that kind of battery, of course." Designed and built by the Arivett brothers of San Bernardino, the car's body shape was tested in Caltech's 10-foot wind tunnel. *White Lightning* is owned by Ed Dempsey, a well-known exponent of electric vehicles who says he is "trying to bring people a new and exciting image of the electric car, one that shows electric power is practical." With the car newly outfitted with special nickel-hydride batteries, Dempsey plans to break his own record.



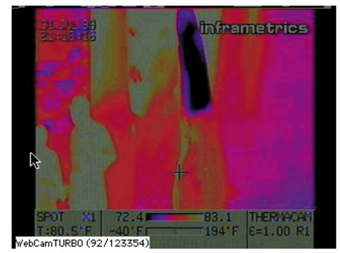
Above: Caltech astronomer Michelle Thaller (left) and Huntington botanist Kathy Musial (right) with the ***Amorphophallus titanum*** behind them in full bloom. Thaller appears to have gotten a fresh whiff of its stench. This specimen was donated to the Huntington by Mark Dimmitt of Tucson, Arizona, who raised it from a seed in his greenhouse. Left: A 1924 bloom in the Botanic Gardens in Buitenzorg, Java. The central spadix can grow up to 10 feet tall. The species was discovered in the Sumatran rain forest by Italian botanist Odoardo Beccari in 1878, who sent seeds to the Royal Botanic Gardens in Kew, England. When it first bloomed there in 1889, at least one lady allegedly swooned from the odor.

Little Library of Horrors

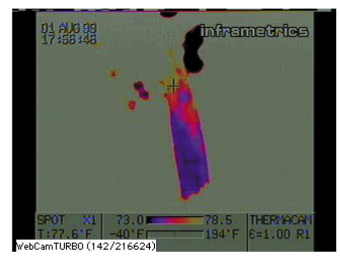
The total eclipse of the sun didn't happen until nine days later and on the other side of the planet, but a strange and interesting plant caused a sensation at the Huntington Library, Art Collections, and Botanical Gardens anyway. Bearing a more than passing resemblance to Audrey II, the bloodthirsty plant from the hit musical *Little Shop of Horrors*, a rare Sumatran species named *Amorphophallus titanum* (Latin for "large, shapeless… well, you know") bloomed briefly on Monday, August 2, sparking a media blitz not unlike the fictional Audrey's. Specimens have bloomed only eleven times in the United States, and this is the first in California, so the saturation coverage drew tourists like flies—entirely appropriate as the plant is known in Indonesia as the Bunga Bangkai, or "corpse flower," because of the reek it emits to lure its pollinators: dung beetles, sweat bees, and other feasters on the fetid. The line of human lovers of the pestilent was two hours long that day. Smelling the miasma, chiefly compounded of dimethyl disulfide and dimethyl trisulfide, was like sticking your head in a dumpster behind a Chinese restaurant—rotting bok choy, in other words, with a hint of exotic spices. (Odor is subjective, of course—other descriptions range from "dead possum" to "old sweat socks.") And the plant itself was a sight to behold: nearly six feet tall from the bottom of its stem to the tip of its fleshy, maroon spadix, which looked like a giant lipstick and at whose base thousands of flowers proper lay, protected within a green, cabbage-leafy sheath called a spathe. When the flowers bloomed, the spathe opened out away from the spadix like an inverted umbrella or a radio-telescope trained on the zenith.

The Araceae family, to which this nosesore belongs, has a curious property—the spadix can heat itself up to as much as 40° C, or 104° F, to help diffuse the noisome seduction. (Araceae are diverse and widely distributed, and include philodendrons, calla lilies, the jack-in-the-pulpit, and, perhaps most tellingly, the skunk cabbage.) The hot spadix acts like a chimney, creating a convection current that entrains the scent molecules and lofts them far and wide. On the day it bloomed, one observer (olfactor?) got a momentary whiff on Lombardy Road, a good half-mile from the plant. "According to anec-

Above: A few of the more than 76,000 people that saw the plant in the 19 days it was on display. Left: Thaller and the video camera on Friday, three days before the bloom. The black thing behind her is the video monitor that displayed the infrared image to the crowd. Right: The image was also broadcast live over the internet. The color bar in the bottom center of the image shows the temperature scale; the "T:" in the lower left corner shows the temperature at the +-shaped cursor. On Saturday (top), the spadix was still relatively cool, but the spathe was heating up. By Sunday (bottom), the spadix was beginning to show heat variations. On Monday, the site overloaded.



LIVE: "corpse" flower in infrared light



LIVE: "corpse" flower in infrared light

dotal information I've received from colleagues, waves of heat have been seen in other *Amorphophallus* species, but not in *titanum*," says Kathy Musial, the Huntington's curator of plant collections. "*Titanum's* odor is well known to come out in waves, so it makes sense that the heat would as well." (In fact, one teenager christened the stinker "the plant that farts," and the crowd's reaction when a fresh pulse hit the air was quite amusing to see.) In order to find out if *titanum* pulsated heat as well, Gail Shair, special projects coordinator for the botanical gardens, asked her father, Fred Shair, who had been at Caltech and JPL since 1965, if he knew anyone who had an infrared camera. He put her in touch with Caltech infrared astronomers Michelle Thaller, staff scientist on SIRTF (Space Infrared Telescope Facility), and Michael Bicay. Thaller, who studies massive binary star systems and is also in charge of educational outreach, has a portable 8-14 micron mid-infrared video camera that she uses for public demonstrations. "It's a very popular trade-show kind of thing," Thaller says. "Kids love it—we give them ice cubes, and they draw on themselves, and it shows up blue. Then I might as well leave, because they don't pay any more attention to me!"

The infrared camera was set up on Wednesday, July 28, and the video feed, which was displayed on a monitor next to the plant and broadcast live on JPL's Web site, became part of the attraction. (The Huntington's Web site, which linked to the JPL feed, had 205,228 hits on August 2.) Thaller, who had to babysit the equipment anyway ("This is not how I planned on spending the end of my week," she said bemusedly), did her outreach thing, explaining to the crowd what infrared light is, and plugging JPL, NASA, and SIRTF, whose logos were prominently displayed. By mid-afternoon Sunday, a few hours before the bloom began to open, there was already a five-degree temperature difference between the tip of the spadix and the place where it emerged from the still-furled spathe. What happened the next day is still a mystery, however—some bystander apparently pushed a button he shouldn't have, and the video recorder, which had worked fine on Sunday, taped two hours of random TV channels on Monday.

But there will be other chances. John Trager, the Huntington's curator of desert collections, attempted to hand-pollinate the plant. The fruit is now setting, but the greenhouse staff will have to wait several more weeks to find out if there are seeds within. And if not, says Musial, there are fifteen or so smaller specimens in pots, awaiting their turn in the limelight. □—*DS*

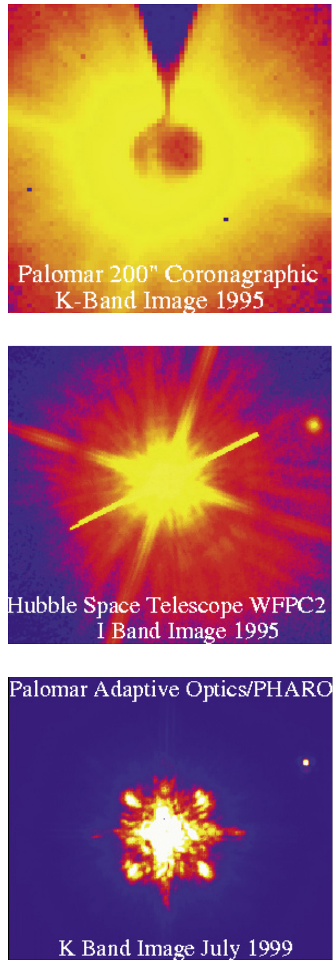
Below: A peek down the spathe at the flowers within. Each plant has a few thousand male flowers and several hundred female flowers, but the female ones bloom first to prevent self-pollination. As this *Amorphophallus* stood alone, the curators attempted to self-pollinate it by hand. The loop of string marks the pollinated region.

CALTECH JOINS EFFORT TO PUT ASTRONOMY IN FOCUS

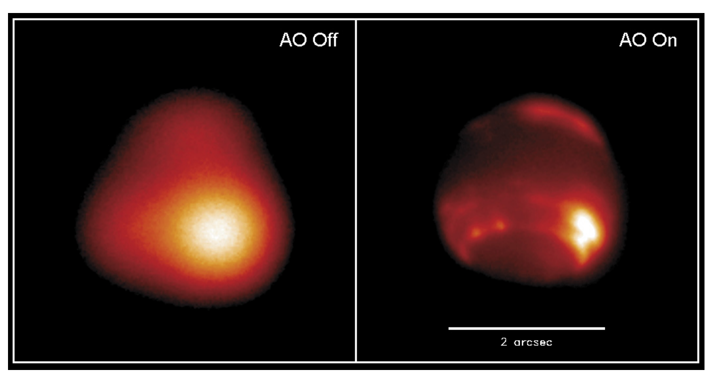
The Institute has signed up to participate in a multi-institutional effort—funded by the National Science Foundation's National Science Board—to advance the burgeoning field of adaptive optics. The project involves establishing a Center for Adaptive Optics at the University of California, Santa Cruz, to conduct research, educate students, develop new instruments, and disseminate knowledge about adaptive optics to the broader scientific community.

The use of adaptive optics compensates for changing distortions that cause blurring of images—turbulence in the earth's atmosphere, in the case of astronomy—and can give ground-based telescopes the same clarity of vision that space telescopes achieve by orbiting above the earth's atmosphere. Depending on the size of the telescope, adaptive optics technology will make images 10 to 20 times sharper, giving scientists a much better view of objects in space.

As one of 27 partner institutions, Caltech will bring together faculty from astronomy, planetary science, and physics in an effort to advance the use of working adaptive optics technology at the 200-inch Hale Telescope at Palomar and the two 10-meter Keck Telescopes. As these telescopes are among the largest in the world to begin with, the returns gained by fitting them with adaptive optics are proportionately large. The Caltech team will be led by Michael Brown, assistant professor of planetary astronomy, and will include Shri Kulkarni, Chuck Steidel, Mark Metzger, and Keith Matthews from astronomy, and Christopher Martin from physics. "This effort will breathe new life into ground-based observing by giving us more sophisticated tools to view distant planetary systems," says Brown. "We can learn and experiment at Palomar, then utilize Keck for the really big discoveries." □—*SMcH*



Left: Three shots of a bright star named Gliese 105 A and its faint, low-mass companion star, Gliese 105 C (to its right). The two stars are three arc seconds ($^{3}/_{3,600}$ of a degree) apart. The top shot is a near-infrared (2.2 micron) image made with the Hale Telescope without using the adaptive-optics system. A coronagraphic mask covers the bright star, blocking most of its glare and allowing the dimmer star to be seen. The middle picture was taken at visible wavelengths from the Hubble Space Telescope and did not need a mask, as there was no atmosphere to scatter the bright star's light and obscure the companion, which is now clearly visible. The bottom picture is another infrared from the Hale Telescope, using the adaptive-optics system. No mask is needed, and the companion is sharp and clear—clear enough, in fact, that its near-infrared spectrum could be taken, a hitherto impossible feat. Images courtesy of Ben Oppenheimer (PhD '99).



Right: The Palomar Adaptive Optics Project, based on a bendable mirror with 241 computer-controlled actuators, is one of the strengths Caltech brings to the collaboration. Built by a JPL team headed by Richard Dekany (BS '89) and installed on the 200-inch Hale Telescope, the system takes 500 samples per second of the light from a bright star in the vicinity of the object of interest, and flexes the mirror as needed to remove atmospheric distortion and create images 10 times sharper than otherwise possible from the ground and twice as sharp (because of the Hale's larger mirror) as the Hubble Space Telescope. These views of Neptune were made with PHARO, a multi-purpose infrared camera built by Cornell University, but the system can be used with all kinds of cameras and spectrometers. Under most seeing conditions, the system gives diffraction-limited resolution, meaning the wavelength of the light itself is the limiting factor—as good as it gets, in other words. Images courtesy of Tom Hayward, Cornell.

ENCORE!

Caltech's answer to Tom Lehrer, Emeritus Professor of Literature J. Kent Clark, is poised to make a splash in the recording industry. The lyricist, librettist, director, and one of the founding members of the Caltech Stock Company—a musical-theater troupe and not, as one might expect in this day and age, an investment group—has finally gotten around to reissuing the Stock Company's 1975 LP, *Let's Advance on Science*, on CD. "People have been badgering me to do this for years," he confesses, "and when my wife finally started getting on me too, I knew the time had come." The CD, digitally remastered by Disk Masters (the same outfit that put out the Caltech-Occidental Concert Band CD *TECHnically Sound* last year), "has cleaned up the sound, but it can't improve my singing."

The best-known song on the album is "The Richter Scale," which has received national airplay on *The Doctor Demento Show*, and gets dragged out of the vaults every time there's a really good earthquake. (The song has held up well, but Clark has no plans to add a verse commemorating Northridge. "Everything since Anchorage is anti-climax.") Other classics include "I Never See Stars," a lilting lament about an astronomer who sings, "I never see stars, even when it's clear/I muck about with photographs and paper up to here/ I never see stars, any size or shape/ I only see computers and a million miles of tape"; "That's Not Gneiss," a rumination on disreputable rocks; and "Down at the Burbank," a tribute to the late Nobelist Richard Feynman's favorite strip joint, where he used to doodle quantum physics on the cocktail napkins while watching Newton's Laws in action.

The Caltech Stock Company, an ensemble of faculty, staff, students, spouses, and offspring, flourished from 1955 to 1975, producing, choreographing, and performing 10 full-length shows and innumerable skits commemorating all aspects of campus life. "In that 20 years," Clark chuckles, "only three important events happened. Beckman Auditorium was built, the Ath got a liquor license, and Caltech admitted women undergraduates. The last is the most important." One of those undergrads, Elizabeth McLeod (BS '76), Caltech's first female ASCIT president, can be heard singing "A Nice Girl Like You," which honors their arrival: "What's a nice girl like me doing in a place like this?/ A nice girl like me happens to be fond of physics/ A nice girl like me wants to be an engineer… Wild about a photon, gamma ray or proton/ No *ton* I want to miss, being in a place like this."

Let's Advance on Science is available at the Caltech Bookstore for $8.50, plus shipping and handling. You can reach the bookstore by phone: (626) 395-6161; fax: (626) 795-3156; email: citbook@caltech.edu; or campus mail code 1-51. ☐—*DS*

Heather Dean, senior in engineering, braves the tepid shallows of Throop Pond to test the reliability of a student-constructed bridge. Dean was one of four student instructors for the seventh annual YESS (Young Engineering and Science Scholars) program, which took place over four weeks in July and August. Sponsored by the Caltech Precollege Science Initiative and the Caltech Y, the program hosts 40 talented high school students from underrepresented socioeconomic and ethnic backgrounds to encourage them to pursue careers in science and engineering. As part of the program, students tackle creative problem-solving challenges, take field trips, listen to guest speakers, and attend sessions exploring college life, leadership, and group dynamics.

EMPLOYER OF THE YEAR

At a dinner at the Doubletree Hotel on July 16, Caltech was given one of two annual Pasadena Model Employer of the Year for Working Parents awards. Established this year by the city of Pasadena and the Pasadena Chamber of Commerce, the award honors employers that offer family-friendly policies and benefits. "The selection criteria include such items as the availability and quality of on-site child care, family leave, continuing education benefits, and other things to improve the quality of life for employees," said Chamber President Lynne Hess. The judges included community leaders, chamber members, and city officials. Two awards were given, with Caltech taking the non-profit organization award and Fannie Mae the for-profit one.

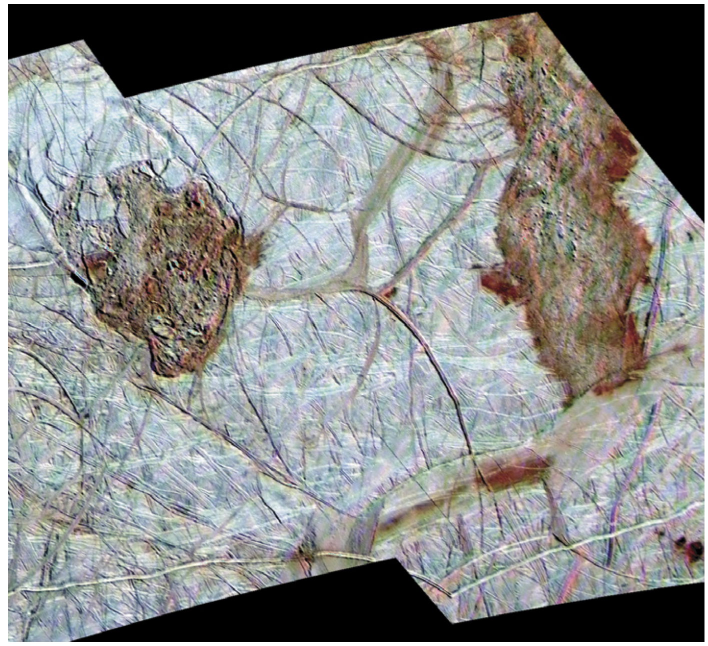
ERRATUM

In the last issue of *E&S*, the 1984 Caltech tomographic map on page 13 should have been credited to Don L. Anderson, Yu-Shen Zhang, and Toshiro Tanimoto instead of Nakanishi, Nataf, and Anderson.

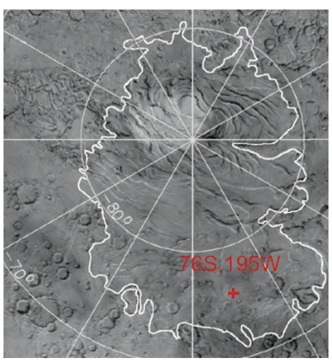
Pizza and Epsom Salts from Galileo

Despite the loss last month of the Mars Climate Orbiter (due to a mixup of metric and English units) the Jet Propulsion Laboratory has a lot going on. The Mars Polar Lander (below), which was going to use the orbiter to relay its data back to Earth, will instead use the Mars Global Surveyor, which has been observing Mars for a couple of years.

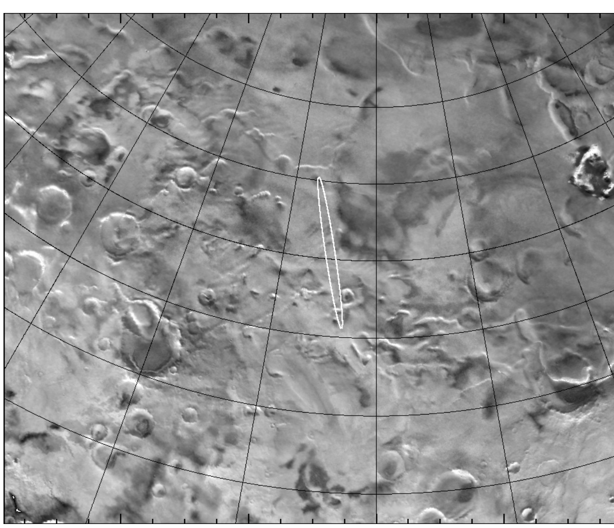
And sturdy Galileo, which also suffered some adversity when its main antenna failed to open after launch, has been orbiting Jupiter and its moons since December 1995, sending back remarkable pictures. Its primary mission ended nearly two years ago, but it's still going strong. Galileo flew by Io again in July and Europa in August, and as *E&S* went to press Galileo was en route to a daring close approach to Io, possibly flying through a volcanic plume.

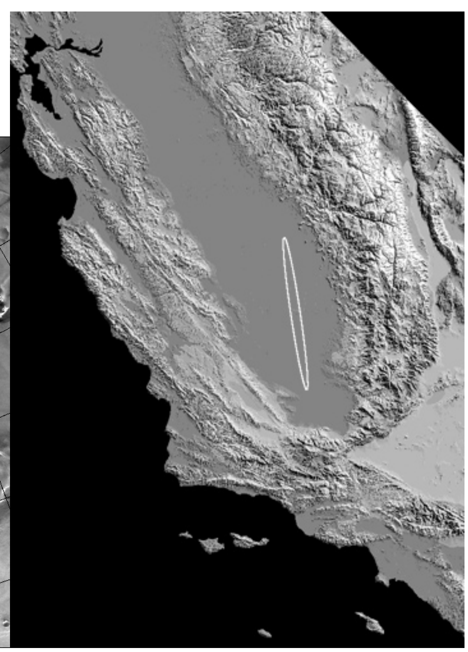


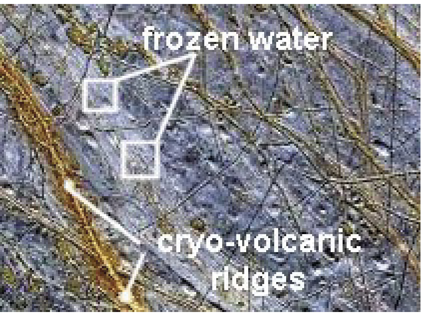
Thera (left) and Thrace (right), rust-colored, 50-mile-wide patches of jumbled terrain on Jupiter's moon Europa, may have come from a liquid ocean or warm ice welling up and cracking the moon's icy shell. Europa's surface is thought to be salty in places (the best spectral match is to magnesium sulfate, better known as Epsom salts), and when warm convecting ice rises up through one of these salty areas, the area will melt at a lower temperature than the surrounding plains. Curved cracks suggest the whole region collapsed at some time. Galileo took these images on August 27.



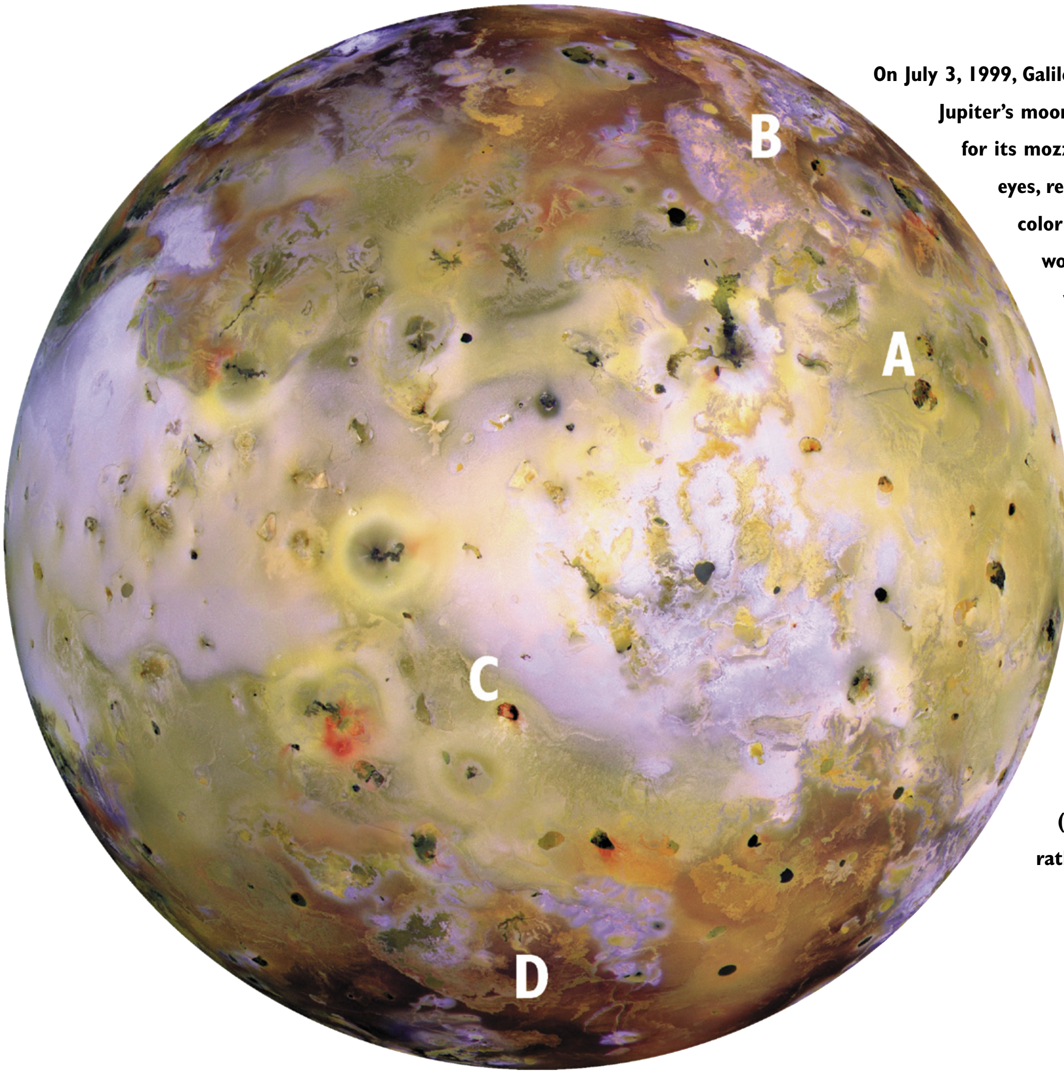
On December 3, JPL's Mars Polar Lander will set down on gentle, rolling plains near the Martian south pole, as marked by the red cross at left. The site, at 76° S latitude and 195° W longitude, is near the northern edge of the so-called layered terrain, outlined in white, whose alternating blankets of dust and ice may provide a readable record of Mars's climate. (A backup site at 75° S, 180° W has also been chosen.) At left below is a close-up of the landing area, showing the 240x20-kilometer landing ellipse, and the same ellipse superimposed on California's Central Valley (right).



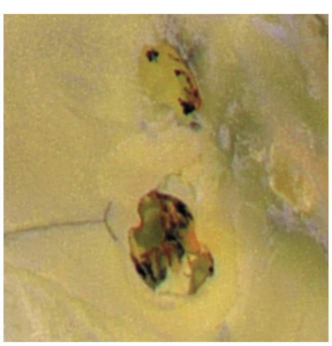


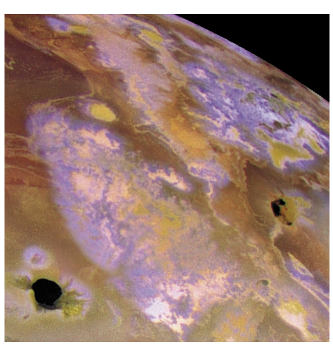


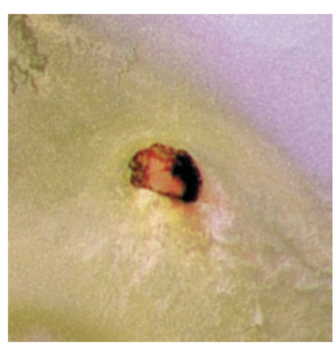
The blue areas in this color-enhanced close-up of Europa's surface are thought to be pure water ice. The brown of the cryo-volcanic ridges may come from underground mineral-laden water percolating through cracks in the crust.

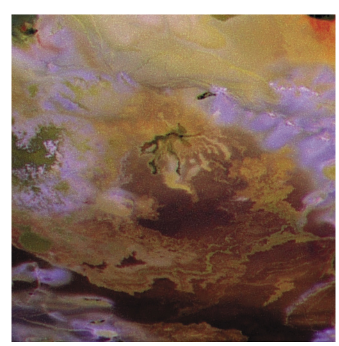


On July 3, 1999, Galileo passed within 81,000 miles of Jupiter's moon Io, known as the "pizza moon," for its mozzarella color and blotches of what, to some eyes, resemble pepperoni and olives. This false-color image, which approximates what it would actually look like to the human eye, revealed some previously unrecognized small-scale features in volcanic Io's constantly changing surface. One of the multicolored "olives" (A in close-up at far left below) suggests that Io's lava and sulfurous deposits are composed of complex mixtures. The bright, whitish deposits in B (second from left) and elsewhere in the high latitudes resemble transparent lids of frost. The red spot at C (third from left below) reveals sharp linear fissure-like features, and the colorful swirls at D (right) might be due to flows of sulfur, rather than silicate, lava.









The universe is just swimming in neutrinos, and if these guys have even the most infinitesimal mass imaginable, it might be enough to account for the elusive "dark matter"—the 90 percent or so of the mass of the universe that we can't see but know must exist, or else galaxies would fly apart from their own centrifugal force.

The Secret Life of Neutrinos

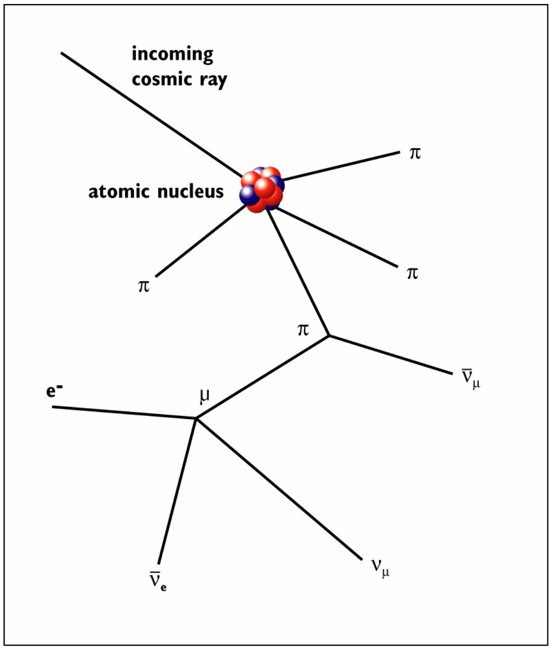
by Douglas L. Smith

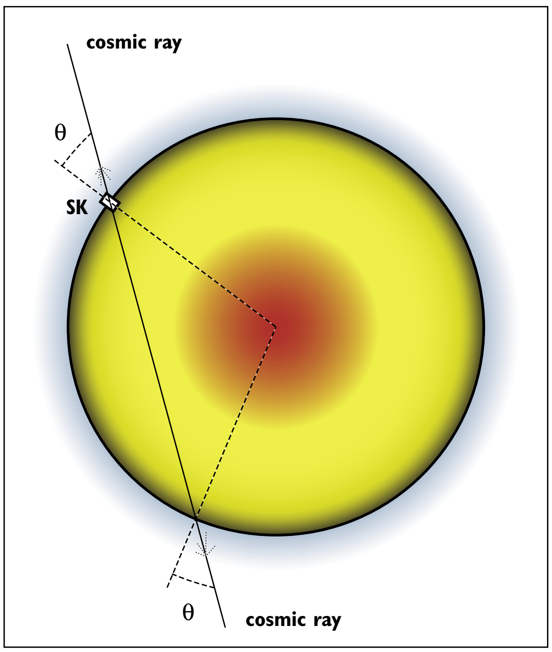
The Palo Verde Nuclear Generating Station is the largest nuclear power plant in the U.S. The plant's three reactors (red arrows) are spaced along a circular arc. The white arrow points to the neutrino detector.

Sit quietly, and count off 10 seconds to yourself. Roughly 200 trillion neutrinos from the sun, from cosmic rays, and from distant supernovas have just passed through you, but you'd never know it. Neutrinos are the ghostliest of subatomic particles. They have no electrical charge, so they're not subject to electromagnetic forces. They're immune to the strong nuclear force, which binds atomic nuclei together. In fact, you could shoot your average neutrino through a light-year's worth of lead bricks before anything would happen to it. These few interactions are a result of the weak nuclear force—a wimpy excuse for a fundamental force that causes neutrons to turn into protons via a process called beta decay, and whose effective range is less than the diameter of the decaying neutron. And until recently, everybody thought neutrinos were massless, like photons of light.

Or are they? The biggest physics news of 1998 was that a Japanese experiment called Super Kamiokande intimated that these evanescent creatures might have just a whisper of mass after all. This set theorists abuzz, because a glimpse of phenomena beyond the so-called Standard Model is the sort of thing that can lead to a Grand Unified Theory of Everything, and eventually to a Nobel Prize. And it set cosmologists abuzz, because the universe is just swimming in neutrinos, and if these guys have even the most infinitesimal mass imaginable, it might be enough to account for the elusive "dark matter"—the 90 percent or so of the mass of the universe that we can't see but know must exist, or else galaxies would fly apart from their own centrifugal force. So now a collaboration headed by Felix Boehm, Valentine Professor of Physics, Emeritus, and including people from Stanford, the University of Alabama, Arizona State University, and the Arizona Public Service Company, hopes to find out how much mass neutrinos have, using the Palo Verde Nuclear Generating Station 60 miles west of Phoenix, Arizona. Nuclear power plants are dandy neutrino sources, pumping out huge fluxes of them in accurately calculable amounts at precisely known energies.

Super Kamiokande didn't measure the neutrino's mass directly—that's not yet possible—but instead measured the difference between the masses of two types of neutrinos. Neutrinos come in three "flavors" mirroring the three kinds of particles produced along with them during beta decay—the electron, the muon, and the tau. When a neutron, which has no electrical charge, turns into a proton (charge +1), the quantum accountants force it to emit an electron (charge −1) as well, in order to preserve the overall charge (zero) of the decay reaction. But the books also have to balance on the number of particles and antiparticles, and now there's a net gain of one particle on the right-hand side of the ledger. Thus an electron antineutrino gets created to keep the auditors happy and the sum of the particles and antiparticles unchanged; the same goes for decays featuring muons and taus. (So whenever we're talking about neutrinos here, we really mean antineutrinos, but that's just too much of a mouthful to keep repeating.) If neutrinos were truly massless, like photons, that would be the end of the story. But if the neutrino's mass is not exactly zero-point-zero-zero-zero-zero-zero-zero-zero-zero to as many decimal places as you care to go, a seldom-invoked clause in the laws of quantum mechanics says that there's a small but calculable possibility that the neutrino will eventually change flavors, due to an overlap in the wave functions that describe them. (The degree of overlap is called the "mixing angle.") The farther a neutrino travels, the greater the odds that it will have changed; but the new particle also has a probability of changing flavors. If you followed the career of this neutrino long enough, you'd see it oscillating between flavors, and the wavelength of the oscillation depends on the difference between the flavors' masses. Super Kamiokande,





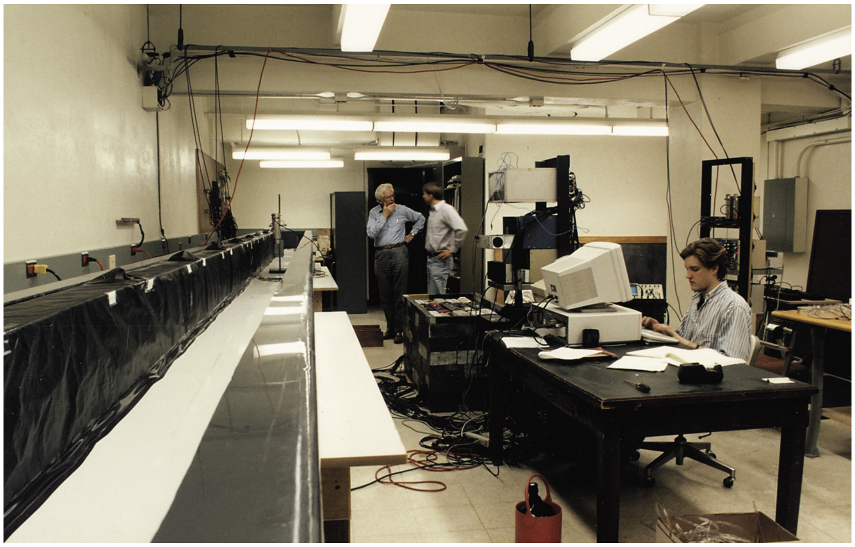
Top: An incoming cosmic ray (usually a high-energy proton, but sometimes something heavier) slams into the nucleus of an air molecule in the upper atmosphere, creating a shower of pions (π) and other particles. Each pion quickly decays into a muon (μ) and a muon antineutrino ($\bar{\nu}_\mu$); the muon in turn decays into a muon neutrino (ν_μ), an electron (e^-), and an electron antineutrino ($\bar{\nu}_e$). Thus for each electron neutrino detected, there should be two muon neutrinos.

Bottom: Cosmic rays bombard Earth from all directions, but shallow-angle particle showers may not reach the surface. Still, equal ratios of neutrinos should be seen in diametrically opposite directions, because the angle of incidence (θ) into the atmosphere is the same. Super Kamiokande (SK) found the expected 1:2 ratio of electron to muon neutrinos coming down from above, but only about 1:1.3 coming up from below.

which was watching for the electron and muon neutrinos created when cosmic rays collide with atomic nuclei in Earth's upper atmosphere, counted equal numbers of electron neutrinos coming from all directions, but fewer muon neutrinos coming up through the planet than down from above. The explanation was that the muon neutrinos taking the longer road through Earth had had more time to change into tau neutrinos. (In 1992, the original Kamiokande experiment had revealed that only about half as many muon neutrinos were making their way into the detector as physicists calculated there should be, but it lacked the directional sensitivity to say from whence the shortfall came.) Super Kamiokande's results indicated a difference between the masses of the muon and tau neutrinos of one ten-millionth of the mass of an electron or less, which is so small it makes one's brain hurt just thinking about it. But if there's a measurable difference in the neutrino masses, then obviously they *have* mass, and that's the point.

And here's where the story starts getting tricky. You might wonder why, if the muon neutrinos were becoming tau neutrinos, Super Kamiokande didn't see tau neutrinos. Well, that's because electrons, muons, and taus differ in their masses but are otherwise identical—they undergo the same reactions and have the same properties. And the mass is the key—because $E = mc^2$, before a particle can spring into existence in a nuclear reaction, there has to be enough energy available to transmute into the particle's mass. Electrons are the lightest of the three, so they are the easiest to create. Muons are 200 times more massive than electrons, but still only one-fifth the mass of a neutron—a piece of cake to make at cosmic-ray energies. Taus, at 3,500 times the mass of an electron, are just too darned heavy. They're only found in the most powerful particle accelerators. But neutrino detectors work by running the beta-decay reaction backward, creating particles that are easier to see. So when the muon neutrinos oscillate into tau neutrinos, they become cloaked in invisibility—they won't register in the detector because they don't have enough energy to create tau particles. Until they oscillate back again at some point further on, they have, for all practical purposes, vanished. It's all in the bookkeeping. We could have used some particle physicists to balance the federal budget back in the '80s.

Nuclear power plants are relatively low-energy systems—at least compared to cosmic rays and particle accelerators—and don't have enough oomph to make muons, let alone taus. Consequently, the Palo Verde Neutrino Detector only sees electron neutrinos. Therefore, what Boehm et al. are really looking for is not the neutrinos, but their disappearance as they change flavors. A straightforward set of calculations based on the reactor's power level and operating characteristics shows how many neutrinos the plant is cranking out. Calibrations done when the reactor is shut down for refueling tell the researchers what the background levels are, and how efficient the detector is. (These calibrations aren't as easy as they might be, because the Palo Verde power plant has three reactors, located at varying distances from the detector, and they're shut down in rotation so that only one, at most, is off-line at any given time.) So if the collaborators see every neutrino their calculations tell them they're entitled to see, then the neutrinos aren't oscillating to an appreciable degree. But if the detector records fewer neutrinos than predicted, it shows that they're oscillating. And the visible neutrinos, taken as an aggregate, should have a specific



Detecting something that has built a career out of not interacting with matter in any form is, shall we say, a bit of a challenge.

All the detector components were tested individually at Caltech before being shipped to Arizona. Here, Brian Cook (at computer), tests the light-transmission properties of a nine-meter-long scintillator cell (at left), swaddled in black plastic to keep the room lights out. Felix Boehm (left) and Andreas Piepke (right) confer in the background.

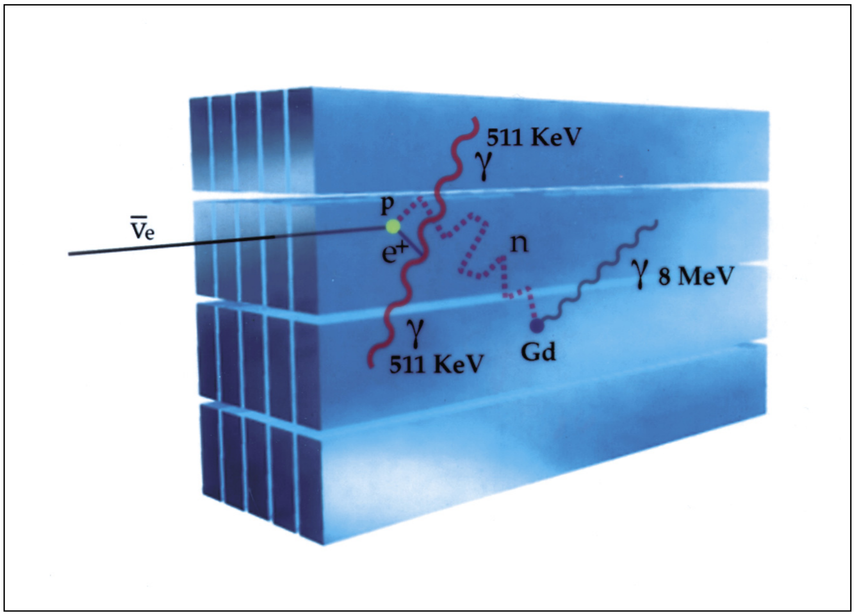
energy distribution that was predicted by Super Kamiokande, because neutrinos with different energies should disappear at different rates.

If the electron neutrino is changing flavors, part of the trick to watching it disappear is to position the detector in the trough of its probability wave. The smaller the mass difference, the longer the oscillation's wavelength is going to be. On the other hand, you don't want to put the detector much beyond the wavelength, because the total neutrino flux falls off with the square of the distance from the source. The farther away you get, the bigger and more expensive your detector has to be. Early results from Kamiokande had shown a slight surplus of electron neutrinos as well as the famous muon-neutrino deficit, suggesting that a small percentage of muon neutrinos were going to electron neutrinos and that a site one kilometer or so from the neutrino source would be a good distance from which to watch this happen. Therefore, the Palo Verde detector was built 890 meters from Reactors 1 and 3, and 750 meters from Reactor 2. Says Petr Vogel, senior research associate in physics and the house theorist for the project, "This is 10 times farther away from the reactor than any previous such experiment, which means that our flux is 100 times less. We have to really push the detector technology in order to see any neutrinos at all."

Boehm and Vogel have been chasing neutrinos for 20 years, starting with an experiment in Grenoble, France, in 1979. (In fact, they wrote the book on massive-neutrino physics.) The field was launched that year at Caltech by Murray Gell-Mann, then Millikan Professor of Theoretical Physics, and postdocs Harald Fritzsch and Peter Minkowski, who did the first calculations of neutrino oscillations. Says Vogel, "Mixing is the hottest issue in particle physics today. Since 1992, four or five other experiments have confirmed that the muon deficit exists. Nobody doubts that neutrinos have mass any more, so the question now is what the mass is and what the mixing angle is. That will be the program for the next decade, to explore this parameter space."

The Palo Verde project is about five years old. It took three years for grad students Brian Cook (MS '93, PhD '96), now at JPL, and Mark Chen (PhD '94); Humboldt Fellows Ralf Hertenberger and Andreas Piepke; postdocs Nick Mascarenhas and Vladimir Novikov; and staff engineer John Hanson to design, develop, and test the detector elements, while member of the professional staff Herb Henrikson, who got his BS in mechanical engineering at Caltech in 1953 and has been a project engineer here ever since, did the nuts-and-bolts design. At the same time, Boehm had to find a site for the project, line up money and collaborators, bid out the construction contracts, and so forth. A year's worth of ground was lost to a competing experiment, subsidized by the French nuclear-power industry, when the initial plan to use the San Onofre reactor, about an hour's drive south of Caltech, fell through—endangered gnatcatchers were nesting on the proposed excavation site. Assembling the detector apparatus and building the underground chamber that houses it took another year, followed by a six-month shakedown period. The detector has been fully operational and taking data since October 1998 under postdoc K. B. Lee and colleagues from Caltech, Stanford, and the University of Alabama.

Detecting something that has built a career out of not interacting with matter in any form is, shall we say, a bit of a challenge. You have to rely on indirect evidence: in this case, the flashes of light produced when a neutrino hits a proton, creating a positron (or anti-electron) and a neutron—as mentioned earlier, the neutron-decay reaction run backward. To maximize the collision rate, the detector contains 12 tons of proton-rich mineral oil, whose average molecular formula is $C_{22}H_{46}$. The oil is heavily laced with pseudocumene, a benzene derivative that has half a dozen easily



"Ah. Triple pulse with the right energy distribution. That's a keeper."

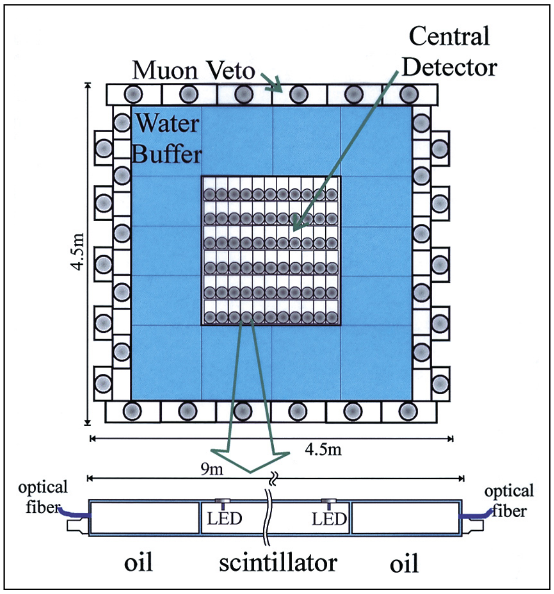
How to catch a neutrino: This schematic shows a portion of the detector array five cells wide by four cells high. An electron antineutrino ($\bar{\nu}_e$) from the reactor hits a proton (p), creating a positron (e^+) and a neutron (n). The positron quickly annihilates an electron (not shown), creating a pair of gamma rays (γ). (KeV stands for thousand electron volts.) The neutron wanders off and is eventually sucked up by a gadolinium atom (Gd), which emits another gamma ray—a whole slew of them, in fact. (For clarity, only one gamma ray is shown.)

excitable electrons per molecule. The positron jangles these electrons as it screams by with an average kinetic energy of three million electron volts (MeV). In a process called scintillation, the excited electrons emit flashes of blue light that are recorded by photomultipliers—light detectors capable of sensing a single photon—and the energy measurement of each flash is sent to a computer. The positron travels about two centimeters, losing energy with every electron it twangs. But to slow down is to die—eventually (within about 30 billionths of a second, that is) it no longer has enough zip to get by its mortal enemy. The last electron it runs into annihilates it, producing two gamma rays at 0.5 MeV, which is the energy equivalent of the mass of an electron or positron. These gamma rays also jangle the pseudocumene's electrons, causing two more pulses of light.

In order to chart the particles' paths, the scintillator oil is parceled out into 66 cells—acrylic-walled rectangles nine meters long by 12 centimeters wide and 25 centimeters high, with a photomultiplier on each end. The cells are wrapped in copper foil so that a flash in one won't trip the photomultiplier in a neighbor. But the gamma rays normally fly through several cells before petering out, so the computer continuously digitizes the arrival time and energy of all the flashes picked up by all the photomultipliers in the array, and scans the lot for "coincidences"—signals from photomultipliers in blocks of up to 15 adjoining cells at the same time—and says, "Ah. Triple pulse with the right energy distribution. That's a keeper."

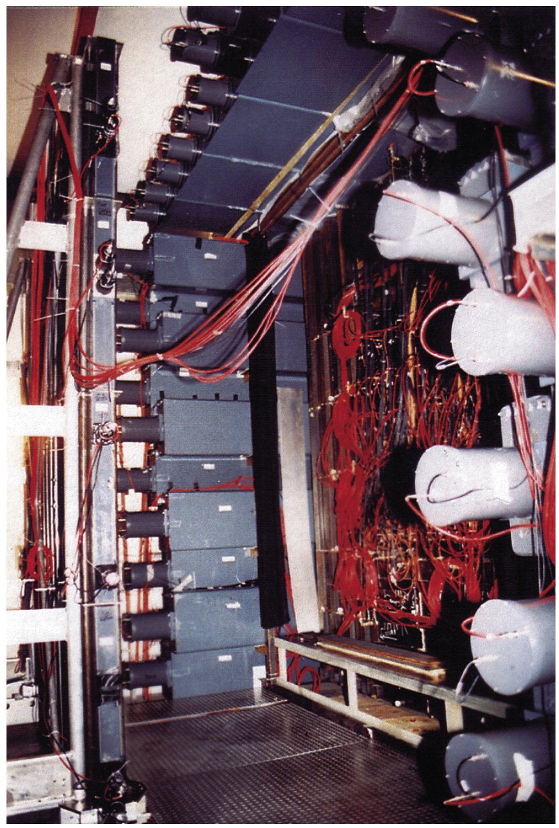
Meanwhile, the neutron plows through the oil, gradually losing steam until it gets absorbed by an atom of gadolinium, which soaks up neutrons like a sponge. (Persuading gadolinium to dissolve in mineral oil is no small feat—like most metals, it's soluble in acids, but uninterested in oil. Some pretty harsh things used to have to be done to the gadolinium to get it into solution, and the result was a dark, nasty liquid that blotted out all light passing through it within half a meter or so. The solution also went bad in just a few months, meaning that the detectors were constantly in the shop for an oil change. So Piepke and Novikov, in collaboration with Bicron, a leading manufacturer of radiation detectors, developed a new recipe for dissolving gadolinium that results in a fluid as clear as water that remains stable for at least two or three years. Bicron now sells the stuff, which has become the industry standard.) Upon catching a neutron, the gadolinium atom emits a fresh cascade of gamma rays at energies of up to 8 MeV. Because these gamma rays are so hopped up, the computer looks for them in coincidences of up to 35 cells at once. A couple of hundred microseconds (millionths of a second) separates the positron's demise and the neutron's capture, and the three-one flash pattern with its set of characteristic energies and delay times is the unmistakable fingerprint of a neutrino.

But lifting that print is not trivial. A bazillion other particles are also zipping through the detector, and they all leave their mark. Says Boehm, "Our detector registers 20 neutrino interactions a day, but we get about 2,000 hits per second from the cosmic-ray flux, plus other background radiation, so it's a very difficult experimental problem. We have to use lots of clever tricks." The Super Kamiokande detector is buried a kilometer deep in a zinc mine to screen out as much background radiation as possible. "Unfortunately," says Boehm, "the Arizona desert has no commercial mineral deposits, so there are no deep mines." Instead, the Palo Verde Neutrino Detector is buried about 25 meters (82 feet) deep—as far down as Caltech could afford to dig. In lieu of a kilometer of rock, the scintillator cells



"Our detector registers 20 neutrino interactions a day, but we get about 2,000 hits per second from the cosmic-ray flux, plus other background radiation, so it's a very difficult experimental problem. We have to use lots of clever tricks."

Above: An end-on view of the detector array (main drawing). The gray circles are the photomultipliers. The muon veto detectors are plastic boxes filled with a liquid scintillator sans gadolinium—muons make gamma rays just like positrons do. There's about an inch of headspace over the liquid in each box, so there are two layers of overlapping boxes along each side wall to ensure complete coverage. At the bottom is a side view of a single scintillator cell. The last half meter on each end of the cell is partitioned off and filled with pure mineral oil to act as an additional buffer. A series of light-emitting diodes (LEDs) down the length of the cell provide standardized pulses of light to calibrate the photomultipliers and, with the optical fibers, keep tabs on the scintillator oil's clarity. Right: The flat gray boxes are the muon detectors and the canisters are their photomultipliers; the scintillator cells are hidden behind the festoons of red cable.



are surrounded by a bank of muon detectors that register cosmic-ray hits. Also called veto detectors, the muon detectors when they go off tell the computer, "Any data you are getting right now is from a cosmic-ray shower. Ignore all inputs for the next 10 microseconds." To help keep costs down, the muon detectors were spares from the MACRO (Monopole, Astrophysics and Cosmic Ray Observatory) project, lent by Linde Professor of Physics Barry Barish and then-Division Chair Charles Peck (PhD '64). Between the veto and neutrino detectors, a 100-ton, one-meter-thick wall of water absorbs neutrons, the other chief byproduct of cosmic rays. And, finally, the computer filters the data through screening programs that reject flashes that aren't energetic enough or otherwise don't look promising.

And there are other subtleties. Samples of all the construction materials had to be vetted by an exquisitely sensitive radiation detector in the subbasement of Caltech's Bridge Laboratory. Ordinary rebar contains a trace amount of radioactive cobalt 60, added to help monitor the production process. "This cobalt 60 is weak for all practical purposes," says Boehm. "But not for neutrino detectors! We had to request special batches of low-cobalt steel to be shipped to us. And concrete is always slightly radioactive, and there's nothing you can do about it. Normally, it contains about one part per million of uranium and thorium, which would have emitted enough gamma rays to choke our detector." These trace elements are found naturally in Earth's crust, so that when you crush rock into gravel, or quarry limestone for cement, they come along. In fact, the product from the local gravel plant was particularly bad. The rock was volcanic, so that it had lots of heavy elements from Earth's interior, and relatively young, so that the hot stuff hadn't had much time to decay.

"The USGS helped us find a marble deposit near

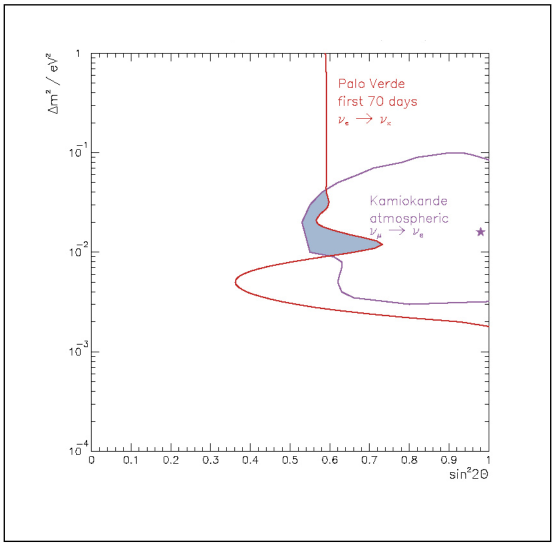
Left: The detector chamber awaits reburial. The access road will soon become a tunnel.
Above: To save money, the tunnel was made from the eight-foot-diameter corrugated steel sewer pipe normally seen on highway drainage projects.

Phoenix that was 10 times radio-cleaner than the local stone. It was trial and error: they sent us lots and lots of rock samples, and we tested them here at Caltech." The Phoenix gravel plant crushed this marble for them, adding about 6 percent to the construction costs. Marble is a soft rock—that's why sculptors use it—and it had never been used in concrete before, so nobody had any idea whether the stuff would be strong enough to support the thousands of tons of dirt that was going to be backfilled onto the roof of the detector chamber. A lot of special testing had to be done at the cement plant before the first batch was trucked to the site. These two factors make the Palo Verde Marble Mix probably the most expensive concrete ever poured—with the possible exception of the night that Jimmy Hoffa disappeared—and certainly the fanciest.

Even with all these precautions, the computer records some 600 megabytes' worth of flashes per day. The data is stored on hard drives at the site, and gets shipped once a day over a fast, dedicated Internet connection to computers at Caltech and Stanford that tease out the fingerprints of the 20 neutrinos a day the collaboration is hoping not to see. These computers also reconstruct the neutrinos' trajectories and energy distributions.

The analysis of the first 70 days' worth of data is now complete. The results are bad news for the neutrinos-as-dark-matter folks, says Vogel. "To be blunt, we do not see oscillations, so the mixing angle cannot be large. And we have moved the mass parameter by a factor of 10 toward smaller masses." These results have almost completely closed the window in parameter space that Super Kamiokande had allowed for electron neutrinos. Thus, it appears that muon neutrinos may mix, but electron neutrinos don't—at least, not to within Palo Verde's detection limits.

But electron neutrinos must mix, because of another long-standing conundrum called the solar neutrino problem. For decades, people have been



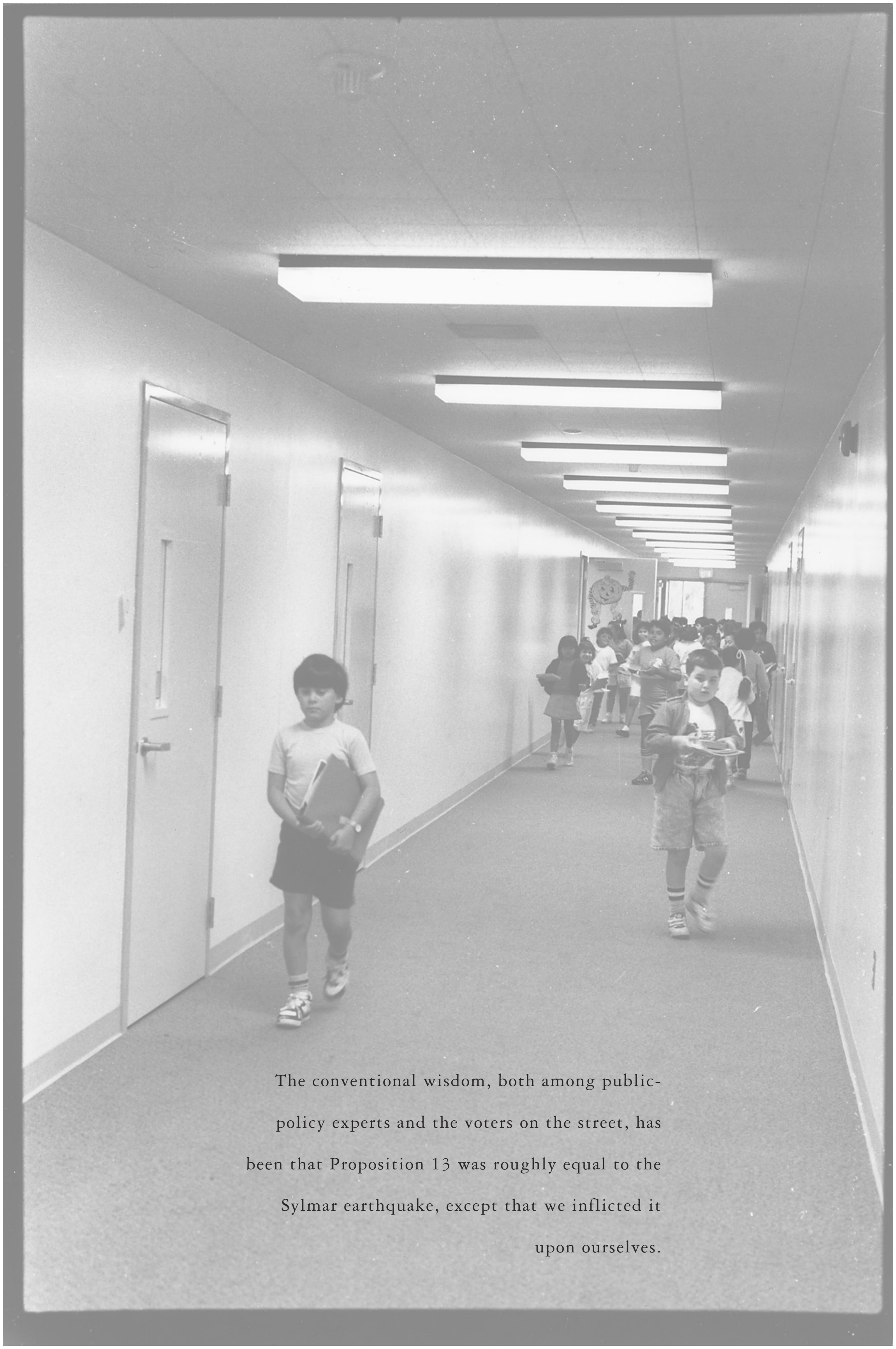
The purple star marks the preferred mixing angle and mass difference derived from Super Kamiokande's results, within the area of experimental uncertainty enclosed by the purple line. However, the Palo Verde results exclude the area lying above and to the right of the red line, so only the blue area remained to be explored. (As *E&S* went to press, the accumulation of additional data had excluded this area as well.) The mixing angle is plotted horizontally, with 0 being no mixing, and 1 being the maximum possible mixing, i.e., a 45° mixing angle. The mass difference is plotted vertically in logarithmic units of electron volts squared.

measuring the electron-neutrino flux from the most powerful nuclear reactor in our neighborhood—our friend, Mr. Sun. These measurements are only coming up with about half as many neutrinos as the solar physicists say should be produced. Either we don't understand the nuclear reactions going on inside the sun as well as we think we do, which is highly unlikely, or else electron neutrinos are disappearing en route to Earth. With a flight path of 93 million miles, even a very tiny mass and minuscule mixing angle would show an effect.

The Palo Verde collaboration will continue to run the experiment through the end of 1999 in order to refine the statistical accuracy of their numbers tenfold—down to the residual uncertainty left in the calculations of the reactor's flux and detector's efficiency. Then the detector gets dismantled. "It's expensive to run," says Boehm. "We have to pay rent to the utility. We have to keep somebody on site to maintain the complex electronics, do all the calibrations, change computer disks, and so on. That person also has to reset all the detectors whenever there's a thunderstorm—we get power outages all the time." You'd think that, being on the premises of a nuclear power plant, they'd have an uninterruptible source of electricity, but no—all their amps come by wire from Phoenix.

The next step, says Vogel, is to explore longer wavelengths. The Caltech group is collaborating on a proposal to build a new detector, called Kamland, down in that Japanese zinc mine. The mine is located near the city of Kamioka, which lies some 40 kilometers north of Osaka near the center of the main island of Honshu. Japan gets about one-third of its electricity from nuclear power, and Kamland will use the 16 nuclear plants on the island as its neutrino source. (If calibrations with three reactors at Palo Verde were tough, calibrating this detector is going to be a real bear!) The plants lie from 100 to 300 kilometers away from the detector, which will contain 1,000 tons of scintillator oil. But even with a detector that size, the collaboration expects to see only about a thousand neutrinos a year, because of the distances involved. Still, this very long baseline will make the experiment sensitive to mass differences 1,000 times smaller than either Super Kamiokande or Palo Verde could see.

The Palo Verde project has been very fruitful, says Boehm. "We have clearly shown that, unlike atmospheric (muon) neutrinos, reactor (electron) neutrinos do not oscillate at these wavelengths. We explored a promising set of wavelengths, and answered a challenging question in neutrino physics while advancing the state of the art in scintillator technology." And they did so for a bargain-basement price: the whole shebang only cost about $2.5 million to build, which is peanuts as particle physics goes. Although the Department of Energy and the collaborating institutions have helped finance the project, Caltech put up a substantial contribution out of the provost's discretionary funds, says Boehm. "Both Jennings and Koonin felt this was an important opportunity, and have been very supportive. We certainly appreciate it." □



The conventional wisdom, both among public-policy experts and the voters on the street, has been that Proposition 13 was roughly equal to the Sylmar earthquake, except that we inflicted it upon ourselves.

The Demise of California's Public Schools Reconsidered

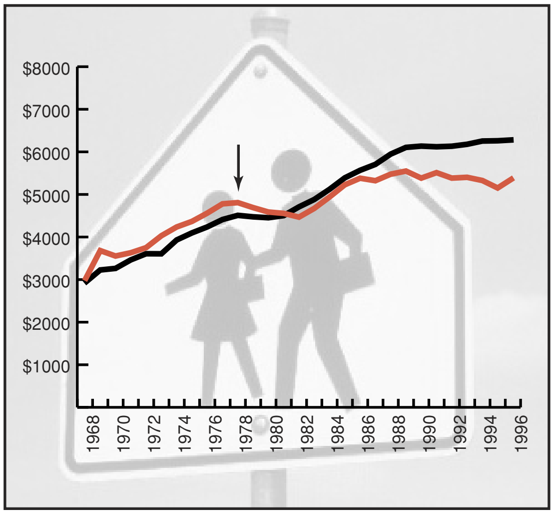
by D. Roderick Kiewiet

I'm not sure when I first got interested in this particular line of research—the fact that I have a son who is now 10 and that we had to make a lot of decisions about his educational future probably got me a bit worried, but I think it actually dates back to when we first arrived in California in the fall of '79. It seemed that all anyone was talking about was Proposition 13, which had passed by a nearly 2-to-1 margin (65 to 35 percent) the previous year. Everywhere we went, it was Proposition 13 this and Proposition 13 that. Some people felt that the voters had just gotten into an angry snit and had irrationally gone on an antigovernment crusade without thinking about the consequences; people on the other side felt that they had been provoked by then-governor Jerry Brown's inane fiscal policies. I don't know if we ever sorted that out, but the conventional wisdom, both among public-policy experts and the voters on the street, has been that Proposition 13 was roughly equal to the Sylmar earthquake, except that we inflicted it upon ourselves.

For those of you who may not know, Proposition 13 was a statewide initiative that rolled back property-tax valuations significantly for then-current property owners. (This has led to huge disparities in tax bills for similar houses on nearby lots, depending on whether the owner bought the house pre- or post-Proposition 13; this has caused a lot of interesting socioeconomic behavior, but that's another story.) Proposition 13 also stipulated that in the future, local property taxes would be calculated at 1 percent of the price at which a property last sold, plus an allowance for a 2 percent per year increase. And, quite obviously, at least for a while, it reduced the amount of income that state and local governments were able to derive from property taxes. Then, in 1979, a companion measure, Proposition 4, the Gann initiative, limited increases in state spending to the rate of inflation plus the rate of population growth—a double whammy.

But public education got a triple whammy, with the third being the *Serrano* decisions. In the original *Serrano* decision (*Serrano v. Priest*, 1971), the California Supreme Court ruled that the existing system of public finance, which was essentially the local property tax, was unconstitutional. The reasoning was that all children in California had a fundamental right to equal public education, but if the funds for that education had to come from the local property-tax base a child living in, say, Baldwin Park could expect substantially less support than a child living in Beverly Hills. The good people of Baldwin Park would have to tax themselves at a rate perhaps 10 times higher than the people in Beverly Hills to support the same level of expenditure in their local school district. *Serrano* forbade local school districts, at least *as* school districts, from spending more per pupil than the state average. (There are ways around this—some wealthier school districts have put together private foundations that have by now raised very substantial sums. No one really knows how much, because not everything they do has to be reported, but according to a recent study, such foundation money supplements spending in many districts by as much as 15 percent.) On the other hand, *Serrano* also stipulated that the state government would give the poorer districts as much money as was needed to bring their per-pupil spending up to the norm. The decision went through the courts for a while; *Serrano II*, in 1976, basically required its very rapid implementation, and by 1982, for all practical purposes, it was in place. So the widespread belief is that the reduction in tax take from Proposition 13 and its companion measures, plus the *Serrano* equalization mandate, led to a dramatic decline in public kindergarten-through-12th-grade education in California.

In a recent book called *Paradise Lost: California's Experience, America's Future*, Peter Schrag, a long-time editorial-page editor for the *Sacramento Bee*,



Left: State and local per-pupil spending on public schools (kindergarten through 12th grade) in California (red) and the average for the rest of the United States (black). The arrow marks the passage of Proposition 13 in California; a decline in spending followed immediately.

It should be noted that the linkage between expenditure levels and student performance, which is usually measured by some standardized test, is tenuous at best. In fact, if you look at the performance of the average pupil in a state, versus that state's spending per pupil, the relationship is slightly negative. In the 1997–98 academic year, for example, New Jersey spent over $10,000 per pupil, New York about $8,800, and quite honestly, on average, their students do poorly compared to places like North Dakota, which spent $5,100 per pupil and whose students do very well. But spending varies all over the map—Wisconsin spent $7,100 per student and Iowa $6,000, and their students are also top performers. California spent $5,500 per pupil; the national average was $6,000.

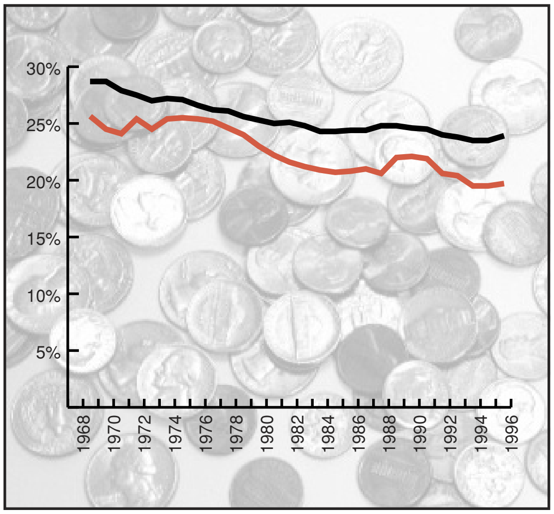
When you look at California's test scores correctly, in my view, the data are not that discouraging. Since the early '60s, the proportion of high-school seniors taking the SATs and the ACTs has gone way up. These used to be elite tests that only the college-prep kids, a small minority in each class, would take. Now nearly everyone takes them. So for as many students to be doing as well as they are is actually, by some definitions, a remarkable accomplishment. When you break down SAT scores by ethnicity, you see that over the last 20 years, there has been—not so much among white students, but among black and Latino students—a very steady and impressive improvement.

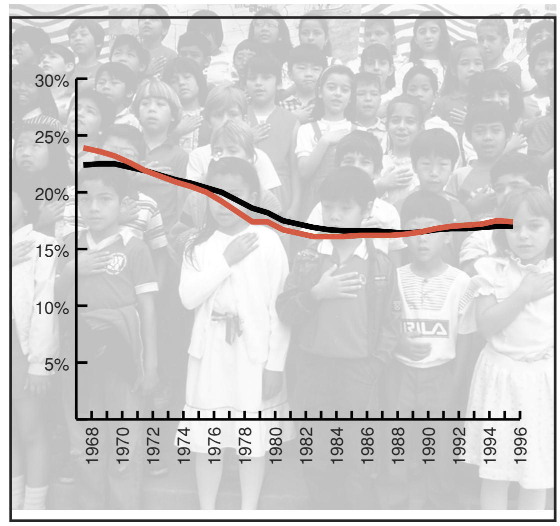
Expenditure data can also be misleading. For example, the L.A. Unified School District employs one of the largest police forces in the state of California. That money shows up on the books as educational spending. And a few years ago there was a proposal to require that 90 percent of the education budget had to be spent in the classroom and not on administration. I can't conceive of that affecting what a school district does. You just call stuff "classroom" and not "administration." So you really have to be careful with these data.

says that "the passage of Proposition 13 serves as a convenient way of dividing the post–World War II era in California between the postwar period of optimism, with its huge investment in public infrastructure and its strong commitment to the development of quality education systems and other public services, and a generation of declining confidence and shrinking public services." I think this captures the view shared by a very large number of people: Proposition 13 is a watershed event that demarcates a much nicer and more glorious past from a fairly troubling present and future. With that, let's take a look at the actual data.

The plot above shows per-pupil spending from 1968 through 1996 in California (the red line), versus the rest of the United States. (I have converted all the data here and throughout into constant 1997 dollars. At this point, I would also like to thank grad student and Excel guru Erik Terreri, who gave me a great deal of assistance in getting all this data together.) You can see that there's reason to believe that Schrag is right—the timing is right on the money. Before 1982, we spent somewhat more, per pupil, than the rest of the country. After that we tracked the other states from below for a while, and then we fell dramatically behind in the late '80s as the recession kicked in. I should mention that by "the rest of the country," I don't mean the national average. With California now containing about 12 percent of the country's population, we've got enough weight to swing the national average around. I mean the average expenditure of all the states except California and Alaska. Alaska has a public-finance system that looks a lot more like Saudi Arabia's than an American state's, so it's not usually included in these kinds of analyses.

If you look at rankings, we were 18th from the top in per-pupil spending in academic 1975; by our nadir (1995), we were 41st. Translated into average class size, we were 49th—Utah managed to get under us. And the performance of Califor-





Right: The percentage of California's total population enrolled in public schools does not differ significantly from the national average.

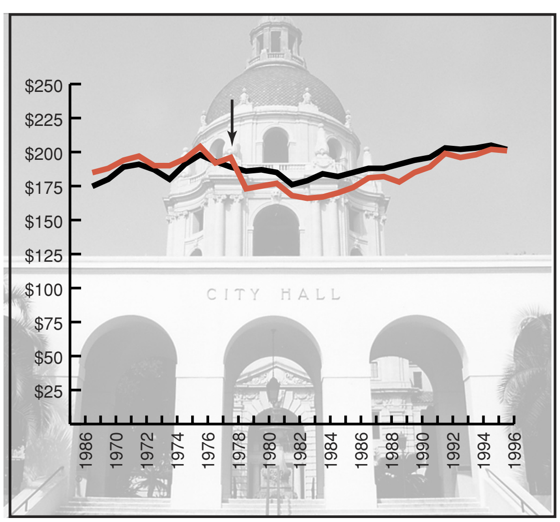
Above: But if you look at the data in terms of spending per pupil per thousand dollars of per capita personal income (a much better measure of how much money is actually available to be taxed), the numbers tell a different story. Spending began a slight downturn even before Proposition 13 passed, but has really remained fairly constant.

Right: Proposition 13's chief effect can be seen by plotting total expenditures by all levels of state and local government per thousand dollars of personal income. Spending in California dropped sharply, but has gradually rebounded as these governments have turned to other sources of revenue.

nia schoolchildren on a series of standardized tests also declined, all pretty much in step with this decline in public expenditures.

But there's another way to look at the level of state and local support for education. The graph above shows spending per pupil in terms of the available tax base, i.e., per thousands of dollars of real personal income per capita. Here you see a different pattern that has a lot more continuity. In fact, we *never*, during this entire period, spent as much per pupil per available resource as the rest of the country. What's going on here? This curve is nearly flat, so even if we've always been a little chintzy compared to the rest of the country, why did spending per pupil in the previous graph suddenly take a tumble?

One possibility might be that we just don't tax ourselves very hard in general. That's not true, it turns out. It hasn't been, and still isn't, throughout this 30-year period. If you sum up all the expenditures made by state and local governments (below), you'll see that before Proposition 13 we were spending a little more than the rest of the

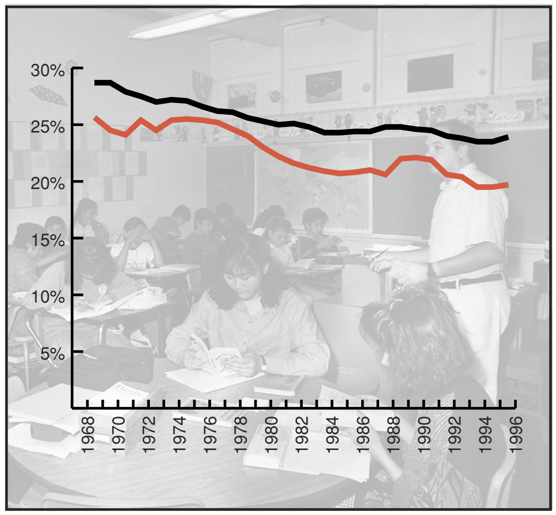


country, and after Proposition 13 we spent less. Proposition 13 hammered us for a year or two, but we had a five-billion-dollar surplus at the time that cushioned the blow, which was one reason why people voted yes on 13 in the first place. They felt that Jerry Brown was sitting on their money. We've been catching up with the other states since then, and now we're about even. So our decline in per-pupil spending is not the result of not taxing ourselves enough, or of not spending enough public money in general.

Another possibility came to me one day when there was a big public event at Beckman Auditorium—I think it was a puppet show—and hundreds of school buses converged on the campus. Caltech was just taken over by six- to nine-year-olds, and I thought, "My God, there's a lot of kids in California!" And so I thought, well, maybe we can't spend as much per pupil because we have so many more of them. Maybe the state has a very young age structure, and there are just a lot more public-school children in California as a percentage of the population. But if you can see the difference between the two lines in the plot above, your eyes are pretty good, because there isn't much. With certain exceptions, like Florida, it turns out that there aren't major differences in the age structures of America's states.

All right then, I wondered, does California send more of its students to private schools? No. It turns out we don't.

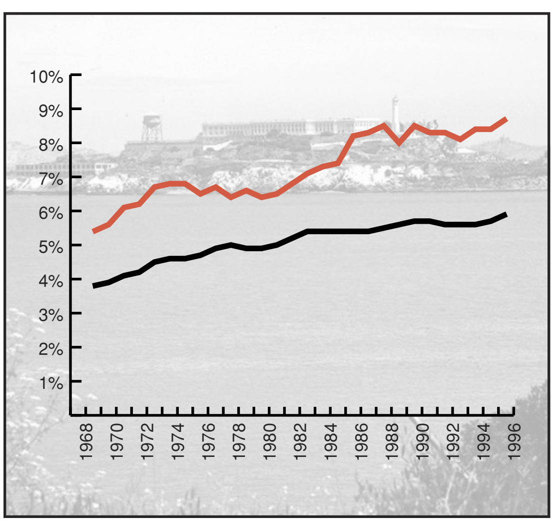
So we're not spending less per pupil because we're spending less on everything. We're not spending less per pupil because we have more pupils per capita. What the figure at the top left of the next page shows is that we're spending less per pupil, basically, because we devote less of our budget to it. The figure charts the combined expenditures of state and local governments, because—California's not unique, but we may be the extreme case—the admixture of state and local funds from program to program is so complicated



Right: California has always (at least for the last 30-odd years) spent a smaller percentage of its state and local budgets on K–12 education than other states.

that figuring out where one stops and another starts is frankly not worth it. In any case, I think you get a more accurate picture by looking at the combination of state and local spending. And, again, you see that we always have devoted, and continue to devote, less of the overall budget to public education than other states. In fact, if we pulled our spending percentage up to the national average, our expenditures per pupil would be a little higher than the national average.

Well, if we've got just as large a budget (adjusted for population, etc.) as the other states, and we're spending less on K–12 education, that means we've got to be spending more somewhere else. And, in fact, the one place where we now and for this entire period have spent substantially more per capita than the other states is law enforcement. (This is a slight misnomer; what I've tracked below is actually cops and prisons. Police and prison expenditures are about 75 percent of the total criminal-justice budget. Judicial administration and court expenses add another 25 percent or so to these numbers.) Right now we spend nearly 3 percent more of our budget—about $8^1/_2$ percent, compared to a bit less than 6 percent for other states—on cops and prisons. If we were to shift that money—about $900 per pupil, or, at 5.7 million pupils, roughly $5 billion per year—to education, we'd basically be up to the national average. Of course, that would mean having a lot fewer police cars on the street and a lot more bad guys walking around, but that's the sort of trade-off that policy makers must engage in. And in California we tend to err on the side of cops and prisons.

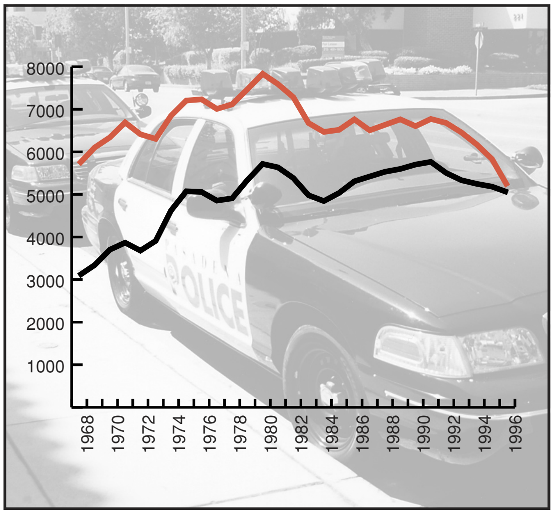


Left: On the other hand, we've always spent more on cops and prisons, such as the now-decommissioned Alcatraz.

In 1968, the California prison population was about 16,000; now it's about 165,000. That doesn't include the very large batch of people in county slammers—to be counted as a prisoner, you have to be sentenced to a year or more. I think we're getting really good at building prisons, by the way. We can put a 4,500-unit, state-of-the-art facility on line for about 330 million bucks. We do the same thing with prisons that the French did with nuclear power plants—we just apply the same plan over and over, like a cookie cutter. There are certain economies there.

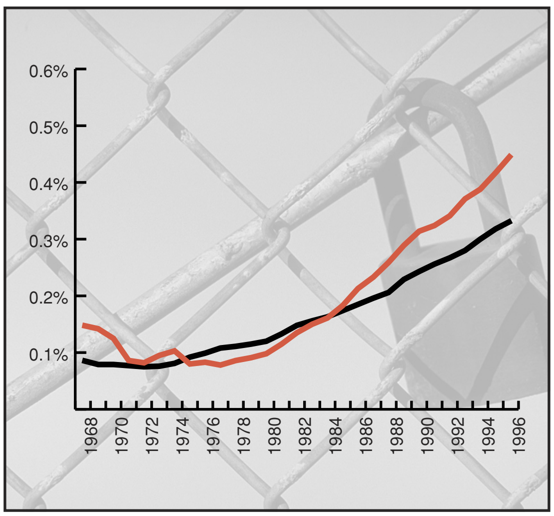
Is this bad public policy? The statistic I always read is that spending on prisons is crazy because it costs $30,000 a year to send a kid to Harvard, and about $75,000 to put him in Avenal. Well, a lot of people have done economic analyses of this, and prison actually looks like a pretty good investment if you're worried about the return to society. These studies say that inmates, were they not in prison, would each be doing some $100,000 per year's worth of economic damage to society on average. That's apart from what disutility you might get out of being hit over the head while you're being mugged. So on an economic basis, we could lock a lot more people up before the marginal cost of locking up the next inmate equals the marginal gain to society monetarily.

But there are other reasons why people are put in jail and kept there, over and above straightfor-

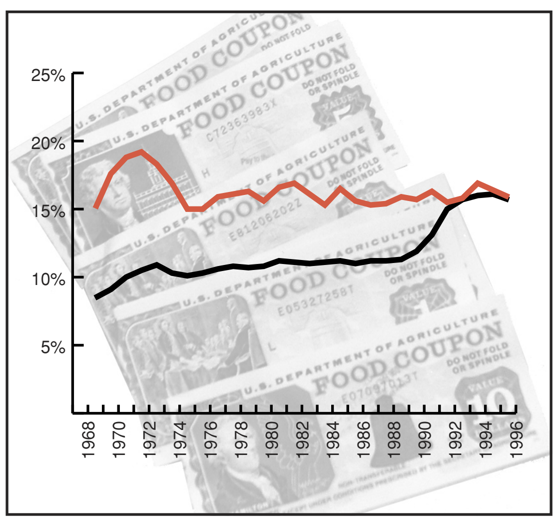


Left: The crime rate in California, as measured by the FBI's Uniform Crime Report Index, has in the past far outpaced the national average. We've recently caught up, however—or caught down, as the case may be.

Below: Is this dramatic drop a consequence of our prison-building binge? We jail a larger percentage of our population than all but a few other states.



Left: "Welfare" encompasses a spectrum of social services, including Aid for Families with Dependent Children (now called Temporary Assistance for Needy Families), General Assistance, Supplemental Security Income, programs to help the blind and disabled, children's services, and foster homes. The hump in the California data from the early 1970s may be an artifact.



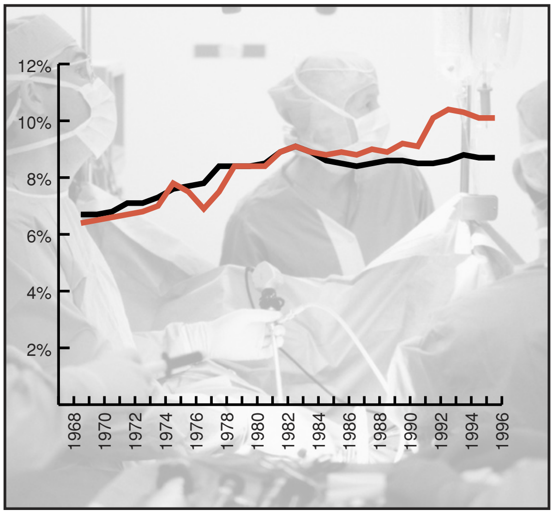
ward economic calculations. When my wife worked as a prison librarian in Connecticut in the 1970s, she had two inmate helpers named Stosh and Phil. Well, shortly after World War II, Stosh had cut his wife up into little pieces, and Phil had murdered a highway patrolman. And all those years later they were still in jail. So there are punitive, as well as economic, reasons for long prison sentences.

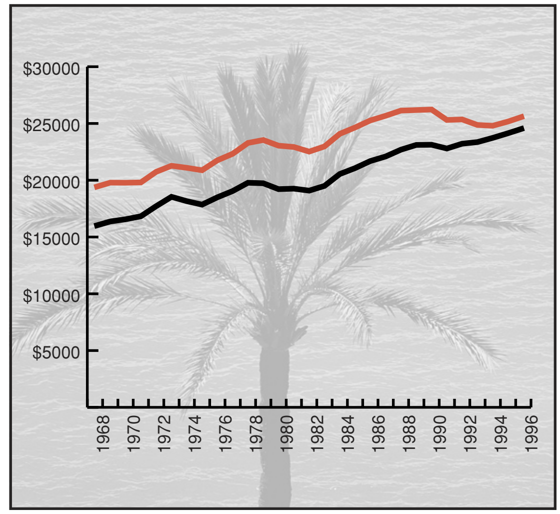
Crime data (top) suggests that California's expenditures are paying off. In 1997, for the first year in history since the FBI began keeping these statistics, the crime rate in California was lower than the national average. (In 1980, by way of contrast, it was about 30 percent higher than the national average.) Crime in California has gone down by about 35 percent over the last five years, as we've locked up very large numbers of people, compared to a decline of about 15 percent for the rest of the country. So we are locking up a lot of guys (left); crime is going down. Whether A causes B, who knows?

Moving on, I also charted spending on public assistance (below). We historically have spent a lot more on welfare than the other states, but in the early '90s they caught up with us. They responded to the recession by increasing welfare expenditures, as one might expect. We didn't do that, as you may recall—we cut back on welfare spending instead. That is, California decreased individual payments. But the caseload grew, so the overall welfare budget held steady. In other words, the total pie stayed the same, but there were more people, so that each person got a smaller slice. In the last couple of years (not shown on that graph), expenditures nationwide have declined as welfare reform has kicked in and welfare rolls have shrunk dramatically.

And finally, I looked at spending on county hospitals and public-health programs. As you can see at the top of the next page, we kept pace with the national average pretty closely until the '90s,

Right: California's spending on health care and hospitals tracked the rest of the nation's fairly closely until the beginning of the '90s.
Far right: While California still epitomizes the good life for many, we aren't as filthy rich as we used to be—the rest of the country is fast catching up.





when we started spending about 2 percent more on health and hospitals. I don't know exactly what happened, but I think it's a substitution effect. People on welfare automatically get Medi-Cal, which is a form of health insurance. But when they leave welfare, they generally get low-paying jobs that don't include health benefits. Then, when they show up at the hospital uninsured, the county eats the cost of their care instead of charging it to the Medi-Cal budget. If you add the numbers together, you'll actually see quite a continuity in overall welfare, health, and hospital spending. It's just that we've shifted money away from the welfare account, which includes Medi-Cal, and toward the county hospital and public-health budgets.

So all our per-taxpayer spending patterns have been very consistent, year in and year out, which brings us back to the initial question: Why has spending per student taken a nosedive since the passage of Proposition 13? The answer is actually fairly straightforward. If you look at the relative size of the tax base in California, that is, our real per-capita income compared to the rest of the country, we used to be quite rich, as shown above right. In 1968, per-capita income in California was 21 percent higher than that in the rest of the country. Today, it's about 4 percent higher. It would be easy to blame bad policy choices by the people who run California, but I don't think that's the problem. It's really part of a very long-term convergence in state incomes nationwide. In 1965, for example, the states of the former Confederacy had, believe it or not, per-capita incomes of about 75 percent of the national level. Now they're up to about 90 percent. And you see similar dramatic convergences across all the states. Per-capita incomes in the rich states are growing, too, but incomes in the poor states have grown faster. And obviously if we grow, say, half a percent less quickly per year over a long period of time, we'll lose ground, in relative terms, as the poor states catch up. So the rich states are still rich, in absolute terms, but they just aren't as rich as they used to be in comparison to the poor states. What this means for us is that the affluent California of 1968 could devote a relatively small share of its resources to public schools and still outspend the rest of the country on a per-pupil basis. The more-average California of 1997 has not changed its spending habits and so falls short. Our history of chintzing out has caught up with us, and we can no longer get more while spending less.

Is *anything* in these data connected with Proposition 13? There's that hiccup around 1980, but that's about it. I think any effect attributable to the loss of revenue associated with Proposition 13 was small and transitory.

Well, what about the third whammy I mentioned at the beginning—the *Serrano* decisions? Have they had an effect? To refresh your memory, the *Serrano* decisions basically mandated equal per-student expenditures, to within $100 or so (it's now to within about $300, because of inflation), in all California school districts. As usual, California led the way with this, but by now there have been 24 other states that have had *Serrano*-like decisions. These things have to wend their way through the courts, so about 11 states—it depends on how you count—have actually implemented *Serrano*-like equalization schemes and by now have had some experience with them. I had Jamie Bishop, a SURF (Summer Undergraduate Research Fellowship) student from Purdue, look at them last summer, and most of those states, if anything, had actually shifted more money *into* education. In 1998, for example, the people in New Hampshire had their local-property-tax basis of funding public education declared unconstitutional, and they came *that close* to going with a state income tax. They somehow managed to avoid it, but they raised another $100 million—which is a lot for a little state like that!—to come up with the additional monies they needed. (They have less

I'm a political scientist, so the theory of education is not my field. But in all the studies I've read on student performance (again, as measured by one of those four or five standardized tests), the variable that's been found to correlate most strongly is the educational level of the student's mother. Once you control for that, the rest of the variables don't explain an awful lot of the remaining variance. And the good news is, overall education levels are higher, particularly in minority populations. Black and Latino children have much higher graduation rates and college-attendance rates than their parents. They are still significantly below white and Asian children, but the gap is closing. We continue to live in a world where each generation of children is somewhat better educated than their parents.

Alan Krueger of Princeton has been analyzing the data generated by the state of Tennessee's massive four-year study, called the STAR (for Student/Teacher Achievement Ratio) experiment. His findings suggest that reducing class size appears to have a small, but persistent and cumulative, effect. In other words, the students who are in small classes as first- and second-graders do a little better at that time, and continue to do a little better throughout the rest of their school years. So former governor Pete Wilson's idea of mandating smaller class sizes is probably a good one.

I know of another study, by Julian Betts at the University of San Diego, which found that homework seems to help. Lots of schools don't require much homework, and it turns out that the students at the ones that do tend to score consistently better. Of course, to make that happen, parents have to make sure that the homework gets done. The schools can roar at the ocean like King Lear, and nothing is going to happen if the parents are not involved. I think the partnership between schools and parents is critical, and a lot of times that's been missing in California. So it's not just expenditures that's to blame. I'm sure many of you have had the experience of looking at your kid's homework and saying, "You're in fifth grade, and you're doing long division with remainders? Sheesh, you should be farther along than that." So you spend a lot of time with your child supplementing the school curriculum, especially in science and math. Unfortunately, that really exacerbates inequalities in opportunities—if your parents are Caltech graduates, you can go to an awfully crummy school and you're probably still going to be fine, at least educationally. Maybe not emotionally or psychologically. But my point is that the parents supplement what's going on in the classroom.

than four percent of our school population, so this is roughly comparable to us raising over $2.5 billion.) Furthermore, over the last 30 years virtually every state in the country has seen a substantial shift in public support from local to state-level sources. These days, about two-thirds of public elementary- and secondary-education money comes from the state. So local property taxes are becoming less tightly linked to educational spending.

To sum up, I think Mr. Schrag and the conventional wisdom are wrong. In the greater scheme of things, the effects of Proposition 13 and its companions on educational spending today are negligible. Instead, I see amazing patterns of continuity, both in the extent to which we're willing to tax ourselves, and the budget shares that various functions of state and local government receive. Budgetary data from many different areas have this quality. There's a lot of weeping and gnashing of teeth every year as the budget battles occur, but when the smoke settles, everybody gets about what they got the year before plus a little more. A friend of mine, the late Aaron Wildavsky, invented a theory about it he called incrementalism. It happens every time—look at what Governor Gray Davis proposed to do with the additional four billion dollars that the accountants say have miraculously accumulated in California's treasury as a result of the strong economy. Guess what? Education's going to get about $1.3 billion of it, which is right in line with the proportion it's always received. So even today, at the margin, when you give the state government an additional four billion dollars and watch 'em spend it, it gets divided up in very much the same manner that the budget always has been. I'm not saying that California's public schools don't have problems, but I can't trace their plight to Proposition 13, or really see Proposition 13 as all that significant an event in the long term of California history.

As the economy improves, we will catch up somewhat with the rest of the nation, but we will never see significant gains until we start spending a larger share of the budget on education. We may be moving that way—education went up a little this last year—but there's no guarantee that that will continue to happen. □

Professor of Political Science D. Roderick Kiewiet got his BA at the University of Iowa in 1974. He came to Caltech as an assistant professor in 1979 while still working on his PhD, which he got from Yale in 1980. He has written numerous papers on Californian and Russian politics, both of which many observers find to be inscrutably Byzantine. He has written one book, Macroeconomics and Micropolitics: The Electoral Effects of Economic Issues*, and coauthored another,* The Logic of Delegation: Congressional Parties and the Appropriations Process*, (with Mathew McCubbins of UC San Diego) for which they shared the American Political Science Association's Kammerer Award for the best book on U.S. national policy. Despite his assertion that he is a latecomer to the study of education, he has long been interested in student welfare. He's served as dean of students (1992–96) and on half a dozen student-related committees, including his current stint on the Core Curriculum Steering Committee. This research is supported by the Haynes Foundation and the Public Policy Institute of California.*

His son goes to a private school.

I think any responsible director in the theater, sort of like a plant breeder, takes these strange genetic instructions from the distant past and makes them into something intriguing and interesting to an audience in the late 20th century, makes them recognizable.

In a reflective moment on the Caltech campus, *Water Forms 1991* contemplates its own image and that of Millikan Library in Millikan Pond.

Jonathan Miller Reflects
(on damaged brains, acting, the afterlife of artworks, etc.)

by Jonathan Miller

The James Michelin Distinguished Visitor lecture series was established in 1992 with a gift from fashion designer Bonnie Cashin to honor her uncle, a distinguished geologist, and to foster creative interaction between the arts and sciences.

The sort of creative interaction that Cashin had in mind is certainly embodied in the career of Jonathan Miller, a neurologist who metamorphosed into a theater and opera director. Miller studied natural sciences at Cambridge University and qualified as a doctor of medicine at University College London in 1959, intending to go on to a career in neurology. "But a funny thing happened on the way to the laboratory," said David Goodstein, vice provost and physicist, who introduces the Michelin speaker every year. "In fact, it was a very funny thing, one of the funniest ever. It was a hilarious satiric review called Beyond the Fringe *that was written and performed by the young Dr. Miller, together with Dudley Moore, Peter Cook, and Alan Bennett." ("Actually, I've tried to tell a few jokes myself from time to time, but for some reason I always wind up back in the laboratory," added Goodstein.)*

After the success of Beyond the Fringe, *first in Edinburgh and then in London and New York, medicine was left behind, and Miller became known in Europe and America as a theater director (from Shakespeare to O'Neill) and opera director (his production of* The Marriage of Figaro *was performed at New York's Metropolitan Opera last season). He is perhaps most familiar to Americans for his television series on PBS,* The Body in Question, *in which his medical background resurfaced. His exhibition* Mirror Image: Jonathan Miller on Reflection *opened at the National Gallery in London last fall.*

So what does neurology have to do with the theater? Jonathan Miller talked about this—and lots of other things—to the Michelin audience in Beckman Auditorium last April.

I feel overawed at the idea of coming to Caltech, particularly as I'm a guilty fugitive from science. I descended into the disreputable morass of the theater and constantly feel remorse at having lost what I believe to be, and what my teachers thought was, a more serious subject. There are still one or two aging professors of mine whom I always cross the street to avoid for fear of meeting their disapproval.

I'll start by talking about a question which I'm often asked: how is it possible for someone who had an interest in the biological sciences, and then in medicine, and then in neurology, to go into the theater? Aren't they completely incompatible? Aren't they incommensurable disciplines? In fact, in some mysterious way there is a curious and almost inevitable connection between the work that I was trying to do in neurology and the work that I continue to try to do in the theater. It has to do with the fact that my interest in neurology and my interest in the brain was never specifically neurophysiological. I was never a good enough mathematician or a good enough biophysicist to be in traditional hard, cutting-edge neurophysiology, though at Cambridge I was taught by some of the greatest men in the field: the late Alan Hodgkin, Andrew Huxley, and E. D. Adrian. So I was, as it were, brought up in the purple of the subject, but embarrassingly recognized at a very early stage that I really wasn't up to the math and physics required to do important neurophysiological research. But in any case, I think that my interest in the brain was almost entirely connected with what I would call "higher orders" of human action. I was really interested in what went wrong with the brain and what went wrong with conduct, with movement, with speech, and with perception. And I recognized that I could probably make a perfectly interesting career for myself in the qualitative observation of patients' behavior, competences, and performance as a result of brain damage.

Beckman Institute mirrors itself by night in what is commonly known as "the gene pool" for the tiled double helix on the bottom. If the pool's surface were truly invisible, with only the unrippled, upside-down Beckman Institute to be perceived, it might serve as Miller's metaphor of the mind.

I undertook to take a medical degree, not because I was interested in helping anyone; I didn't really want to go into medicine to do good. I didn't want to do *harm*, but I knew that a medical degree assured you a ringside seat closer to the action than you could have if you were merely qualified as a neurophysiologist. You were allowed to ask ruder questions and poke your hands into ruder parts than you could if you didn't have a medical degree. I was interested in seeing what happened when the brain was damaged, what it was that people couldn't do, and I hoped that would give me some sort of insight into what went into being able to do the things that we seem not to have to think about.

One of the extremely striking things about human behavior is the peculiar transparency, and indeed inaccessibility, of the apparatus which mediates our performances and our competences. If mine were the only brain in the world, and I didn't have access to other people's brains, which I could see by opening their skulls, then I wouldn't know that I had one, nor would I have any information from my competence or from my experience or from my performances or from my sensations. I would not actually be aware of the fact that all of these things were mediated in some way by some material substance or some material apparatus.

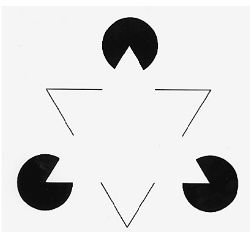
I was interested in seeing what happened when the brain was damaged, what it was that people couldn't do, and I hoped that would give me some sort of insight into what went into being able to do the things that we seem not to have to think about.

In a sense I'm reminded of this rather more acutely by having recently curated an exhibition on reflection at the National Gallery in London. I was struck by the fact that the mirror has been so frequently invoked as a metaphor for the mind, for the reason, I think, that there is nothing to be seen in a mirror except what the mirror reflects—that the mirror only gives you an image of a world elsewhere; it gives you an image of the world of which it is a reflection. And looking into a mirror, try as you can, unless the mirror is flawed or damaged in some way, you are absolutely unaware of the medium which supports the reflection of which you are conscious. The only thing that can be seen in a mirror is what it reflects. You don't see the mirror itself at all, though of course you get these rather peculiar and paradoxical experiences in which, when you are aware of the fact that it is a mirror—if you have circumstantial evidence to the effect that what you are looking at is not a window, for example, but is in fact a mirror and is reflecting something—in addition to seeing what it reflects, in some mysterious way you are also aware of its objectively nonexistent surface.

I was first struck by this about 10 years ago when my wife and I were driving back from Switzerland and stopped off for a rest at a lakeside on the Swiss-French border. And I immediately noticed the peculiar sheen, a shine on the surface of the lake. I found myself asking my wife what to her was an extremely tedious question, and that was, "Why does it look so glassy?" And she said, "Well, because it *is* glassy." And I said, "But there's nothing to be seen on the surface of the lake except a perfect upside-down replica of what's to be seen on the other side of the lake. If you look very carefully, there is no debris floating on the surface, there is no ripple on the surface, there is no deformation of the surface. All that is to be seen is a perfect upside-down reflection." Why, in addition to seeing what was reflected in the lake, did I also see the surface which supported the reflection?

And I then started to bore her even further by conducting a series of informal experiments. I brought up a piece of paper from the foreground, which blocked off the view of the near shore, and I then brought down a piece of paper from on top which blocked off the vision of the distant shore, of which we could see the reflection in the lake, so that now all that could be seen was a sort of letter-box view of the reflective surface. Now, once I had deprived myself of the information that it was a reflection I saw, I suddenly became aware of the fact that all that I could see was an upside-down image, a paradoxically upside-down image of mountains and trees. But in the absence of the circumstantial evidence to the effect that it was a reflection, the only evidence to that effect was that it was upside-down.

Deprived of its context, it was also, I found, deprived of its glitter. Now the sheen of the lake was no longer there, all that was to be seen was what was represented in the lake. I then became very interested in this presence of what I would describe as an illusory surface. It's the counterpart of something which has been pointed out by experimental psychologists for a long time—started by the great Italian Gestalt psychologist Gaetano Kanizsa, who introduced something which has become the logo now for the Exploratorium in San Francisco. You know, the three black disks arranged in a triangular format, in which there are bites taken out so it looks like three Pac-Men. Now in addition to seeing three black disks with wedges taken out of them, you see, as a result of their configuration, something which objectively is not present, which is a white triangle overlying the three black disks, to the point that you can actually see or seem to see subjectively a contour between the edge of this nonexistent triangle and the white background upon which it lies. Here you have an illusory contour.



Now, I believe that something similar is going on when you look at a reflection in a lake and when you look at a shiny surface in which you see an absolutely perfect reflection. When you are allowed to see the entire composition from which you can infer that you are in the presence of something reflected in an invisible surface, you credit that invisible surface with a presence which it otherwise doesn't have, objectively. And this seemed to me to be a perfect metaphor for the mind. Looking at you, there, in front of me, looking up into the lights, all that I can see is what my senses deliver to me. I cannot, by inspecting my own experiences, see the grain or the substance, which actually supports this in exactly the same way as my not seeing anything in a mirror except what the mirror reflects.

I was puzzled at a very early stage, long before I sat on that lakeside, by the strange invisibility and impalpability of the apparatus I was told I had inside my head, which afforded me these experiences and competences I could undertake without having to think about them. I found myself doing sort of Wittgensteinian things: I lifted my arm without thinking what I had to do in order to lift my arm. I knew when I became a medical student that in order to clench my fist, a necessary condition of my clenching my fist was the contraction of the muscles in my forearm. But in no way could I actually bring about the contraction of the muscles in my forearm as a prior condition of my clenching my fist. In fact, paradoxically, it seemed to be the other way around. The only way in which I could get access to the forearm muscles and make them contract was by clenching my fist. I don't really know what I have to do in order to contract my biceps, but I know that the best way of contracting my biceps is to bend my arm against resistance. So, in other words, all of this apparatus which affords me my motor competences, all of this apparatus through which I experience the world, is in fact totally transparent to me. It is totally without physical, visible, palpable properties. And I was puzzled by this gap that lay between experience and the third-person knowledge that I had a brain inside my head which afforded me all these experiences.

So I went into neurology in order to get myself into the best third-person seat in the house, from which to see what the connection might be between having a brain and having experiences. I am still puzzled, in a way that some philosophers in Southern California seem not to be puzzled, by the fact that one of the consequences of having a brain is that one sees red and tastes coffee. Now, it seems to me that there is no problem about what David Chalmers, for example, has called the psychological properties of having a brain: the competences that come from perceptual distinctions, memory, and the sorts of things we can easily reproduce with computers. But there does seem to me to be an absolutely insoluble problem, and I believe it to be radically insoluble, about how it is that this stuff can actually taste coffee and see redness.

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Now, I know that there's no mystery involved; I don't think something magical gets snuck into the system and confers experience upon an otherwise totally material setup. But I think it is probably impossible in the foreseeable future that we will solve the problem of how it is that having this rather unpromising porridge inside the skull can actually yield redness to its owner. There seems to me to be no problem about how it is that having this porridge inside the skull can yield all sorts of abilities to distinguish and press buttons when different hues of redness are exposed to the owner. That's not a problem at all. You haven't got to have an experience in order to do it; you can actually set up a machine which can make such discriminations. But, to quote Thomas Nagel, there is a mystery in the fact that there is something it is like to be us. As he points out, there must be something it is like to be a bat. Well, I think that there is something much more mysterious in that there is something it is like to be us, and I suspect that, even if I had stayed in neurology, I would have remained as puzzled today as some people are not (and I think quite unjustifiably not) puzzled that there is such a thing as redness rather than responses to a particular wavelength of light striking the retina. The problem of redness is extremely odd and one which I think people are far too confident about solving. They believe that ultimately it's an emergent property in the way that liquidity is an emergent property of H_2O molecules put together in a certain way. John Searle at Berkeley believes that consciousness emerges in exactly the same way as liquidity or conductivity emerge from certain configurations of physical matter.

Another example cited is bioluminescence. We didn't know how it was that a firefly or a glowworm could switch lights on and off. Well, we solved that; we know that an enzyme called luciferase catalyzes an oxidation reaction, which releases a photon. No problem. But unfortunately there's a curious tendency to try to equate bioluminescence and consciousness as if, in fact, consciousness were simply a brainglow, an observable thing, an emergent property which came out of putting together matter in a certain way. So we have this weird, paradoxical situation, in that we know that it's nothing other than matter put together in a peculiar way, but the idea that matter put together in a peculiar way can yield content and excitement and things like redness and coffee seems to me to be beyond our understanding at the moment, and I suspect beyond our understanding at any future moment that we can imagine.

Nevertheless, it seemed worthwhile to go on in neurology even if, in fact, the problem of experience, the problem of what the philosophers call *qualia* would remain insoluble. There was lots of other work to be done, and it was not, as Patricia and Paul Churchland at UC San Diego insist, a counsel of despair to say that this would never be solved. There's plenty of work to be done; we will approach this problem asymptotically and never arrive at it, but en route to it, all sorts of extremely interesting things will be solved with regard to our ability to calculate, to remember, to distinguish colors, and so on and so forth. And also to raise our arms without being able to contract our muscles knowingly.

Now, what on Earth connection could all that have to the theater? Well, one of the things which became clearly apparent to me was that the work I did as a diagnostician in neurology sensitized me to the demeanor of people. A good clinical neurologist could probably do 30 percent of the diagnosis by the time patients have got from the door to the chair, and could do it without having to use any sort of technical instrument but by merely watching the demeanor, the behavior, the gait, the facial expression, and the way in which they address him and give an account of their illness. In fact, the performance of a patient sensitizes you to behavior in a way that is completely transferable, wholesale transferable, to the theater.

What are we doing in the theater? We are getting people to pretend to be people they are not, which is very hard to do. You watch actors down in the canteen after they have rehearsed, and usually rehearsed very badly, trying to be someone they're not, but down in the canteen they are totally at ease with themselves when they order coffee and talk to their fellows about what they're going to do next. One is immediately struck by the peculiar discrepancy between being yourself and pretending to be someone else. And what is it that actually happens, as you rehearse and get better at being someone you are not, starts to concentrate the mind wonderfully on the problem of what it is to be oneself in the first place. Once you start getting people to pretend to be someone they're not, you have to start breaking down the modules of behavior, and it focuses your attention on the spontaneous performance of self, because you're actually asking people to pretend to be selves that they're not. And you can watch the incompetences, the failures of performance, of an actor in exactly the same way as you watch the failures of performance of a damaged patient. I'm not saying that actors are damaged, but actors are "damaged" until such moments that they have actually gone onto the stage with what they believe to be—and what the audience agrees to be—a satisfactory performance. There is a long period of invalidism between the moment when

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Miller's production of Janácek's *Kátya Kabanová* was performed at the Metropolitan Opera in 1991, 70 years after its premiere in Brno. Had the opera entered its "after-life," or was the New York audience close enough in time to share the sensibilities of the audience for which the work was intended? (Courtesy of the Metropolitan Opera)

they are given the text and yield the final performance. And by observing that long invalid period when they are handed a text consisting of lines which have not occurred to them but for which they have to give the audience the impression of uttering and meaning them—in that long invalid period, by watching what it is that goes into that incompetence, you learn something about what competence itself consists of.

So there was an almost seamless transition for me. I found there was no awkwardness or difficulty or inconsistency about having watched damaged patients whose motor systems were off, damaged patients who were unable to recognize their relatives, and watching actors. All of these things which I saw in neurology seemed to have a bearing upon the things that people were doing when they were rehearsing. I also found a very interesting reciprocity between being a doctor and being a director: in addition to finding that the work of observation—which I had been trained to perform as a neurologist—lent efficiency to my directing, I also found that the observations I made in the rehearsal room could feed back into clinical work. I found myself going back to the wards and seeing things my clinical colleagues had missed. People often say, "Well, of course, the reason why a doctor finds it so easy to be a director is that you're dealing with mad people, disordered people. We all know actors are potty in some way." It's got nothing to do with that; actors are not potty; actors are perfectly ordinary and often rather humdrum people who sometimes spring into a more colorful existence when they're pretending to be someone other than themselves. But that's not the appeal. The appeal is not that you could help people—actors—who are damaged, but rather that, in seeing people who can't quite get round being someone else, you are actually focusing on what goes into being a self in the first place. So I went into the theater. I found it a very intellectually profitable way of simply extending the work that I was trained for in the years that I had actually been studying clinical neurology.

The rest of my work time in the theater I spent working on what one could loosely call "the classics." I worked on texts, on scores, which are inherited from the relatively distant past, works which probably have had a longer posterity than their makers could have imagined. It's extremely unlikely that Monteverdi and Shakespeare ever in their wildest dreams imagined that their works would be bequeathed to others who were so fundamentally and recognizably different from them and from their audiences. It's very hard to put ourselves back into the imaginations of people in the 16th or 17th century and to conceive the notion of posterity as visualized by them. We know that most works were, in fact, composed for the occasion, so we have this rather peculiar and interesting philosophical problem of what to do with works intended for an occasion, and which have been retrieved and revived and undone by people who are utterly different from the people for whom the works were intended.

The phrase I constantly invoke in describing this is what I call the "afterlife" of plays and operas. With very few exceptions, I think you can say that almost all forms of art have what you might call their natural life—a life for which they were intended, an audience for whom they were intended. And then at some time which is very difficult to date accurately (and it may not even be reasonable to *want* to date it accurately), they enter something which you could loosely call their afterlife. They are now being seen and visualized and retrieved and valued and reconstituted for reasons completely different from the reason for which they were composed and enjoyed at the time they were done. So there is a deep procedural problem about what to do with these works from the distant past, which fall into our world like meteorites from another part of the cosmos. I became fascinated by the problem of how to perform something when you don't know what it was intended for originally and what the sensibility was of those to whom it was delivered.

I sometimes think that it's very similar to the distinction that was made in 1909 by the geneticist Wilhelm Johannsen, who distinguished between genotypes and phenotypes. What you have in the form of a text or a score is something like a genetic instruction. It's a promissory note with a view to something which will be created by obeying the instructions. But what in fact is created as a result of following the instructions depends, as it does in biological organisms, on the environment for which those instructions are delivered. Subsequent performances of the dramatic phenotype will often be profoundly different on successive performances from the performance that was generated by the same genetic instructions at the origin.

This poses a deep and interesting problem about transformation and interpretation. Audiences—particularly in the United States where they're very conservative about opera—who believe that there is a standard phenotype which ought to be preserved at all costs, become terribly restless when it's not preserved. They believe that the genotype tells you what the phenotype should look like, and that the phenotype should be preserved as it was at the origin. But of course very few people have any idea what the original archetypal phenotype looked like. We don't know what the first night of *Twelfth Night* looked or sounded like at all. All that we have is this sort of rough DNA which has come down to us imprisoned in literary amber, which we can, as it were, prise out and put into modern actors and create a Jurassic Park of modern drama. There's no way we can ever backtrack to the original phenotype because we don't know what it looked like, and we certainly don't know what it sounded like. There are only very incomplete reports of what the earliest performance of *The Marriage of Figaro*, for example, was like. There's no way of knowing. And indeed if there were a way of knowing, there is a deep perceptual problem about how you obey the instructions of the phenotype as exemplified by a record.

Let me tell you what I mean by that. The problem is raised most acutely by forgery, which, in a way, is the prototype of the faithful performance of the original phenotype. Now, doing operas is a very expensive business, so you cannot afford to junk the performance of any given production after the inaugural run. You've spent so much money costuming it and designing it and simply putting it on the stage the first time that you have to go on reviving it at successive intervals. What you do is write down a series of parallel instructions, in addition to the score you inherit from Mozart or from Verdi. There's a prompt book, which says: "A moves downstage left, sits down, and turns contemptuously towards B." And after the first year, by reading those circumstantial prompt book instructions, you can reconstitute an approximation of that inaugural phenotype of the performance of that particular production. After about four or five years, when the instructions in the prompt book are no longer being read by someone who was there at the time they were written down, it becomes extremely problematic as to what those instructions really mean. You can work out mechanically what they mean. A little arrow penciled in shows A moving downstage left, and you can say, "Well, darling, what you do is you move downstage left," and then the actor or the singer will turn to you and say, "Well, *why* do I move downstage left at this point?" And you look it up and say, "Oh it doesn't say; it doesn't say why."

What would have happened if we had had a perfect, faithful videotape of the first night of *Twelfth Night*? Well, there is an interesting

Miller directed *Le Nozze di Figaro* for the Metropolitan Opera's 1998–99 season. The "conservative" American audience, if it thought it was seeing something close to the original Mozartean production of 1786, was wrong but apparently pleased. (Courtesy of the Metropolitan Opera)

perceptual problem in copying a performance which is visually in front of your eyes and ears at the time, and there is a deep procedural problem about what goes into copying something. To use Nelson Goodman's term, what do you think the example exemplifies? Which aspect of it is important? More often than not, you may have at your disposal in the first three or four years an assistant or a stage manager who was present at the time of the original performance who could say, "Oh, what you see on the videotape here does not exemplify what people wanted in that inaugural performance; it's a fault. It's something which is not a realization of what was intended. It's a genetic error, a misprint, a mistranslation of the instructions."

Now, what happens when people consult the videotape 15 or 20 years later? How do they know which part of it is, in fact, the part which ought to be copied? They have to start looking at it with a view to what they think is interesting in the example, and this brings me back to the question of forgery. Forgeries are by definition the prototype and the epitome of the faithful phenotypic reproduction. All forgeries become apparent after about 30 or 40 years. Why? The most interesting illustration about that is the story of Van Meegeren's forgeries of Vermeer during the '30s. Van Meegeren was an envious, failed artist, who felt that the only way in which he could attract attention, or prove to a disbelieving art world that he was, in fact, a genius of some sort, was forgery. Since people didn't like his original work, he said, "Well, I will show how good I am by reproducing a work of someone who is widely admired, which will thereby prove that I'm as good as he is. I will do Vermeers."

Now, there's no point in doing Vermeers everyone knows already because they would obviously be copies of Vermeers, so what he had to do was produce original Vermeers. When he delivered his original Vermeers, the art establishment in The Hague was taken in by the paintings and said, "These are indeed interesting examples of the early Vermeer of the period of *Jesus in the House of Mary and Martha*" (which you can see in the Edinburgh Gallery). And then something rather fascinating happened: he stupidly sold a couple of his pictures to the Germans, so that in 1945 he was had up in front of a Dutch court for collaboration, for selling a national treasure to an occupying army. Van Meegeren now had to say, "Well look, no, those are in fact by me. I was not selling Vermeers. I was only selling Van Meegerens and who cares a damn?" The court then said, "Well, prove it." So he painted another Van Meegeren. Now here something deeply intriguing happened, as Nelson Goodman points out in *The Languages of Art*. In the knowledge that these two or three he had done were, in fact, Van Meegerens, the genuine Vermeers, which were previously seen as imperceptibly the same as his forged Vermeers now became quite clearly distinguishable. Now, this isn't because people were just being wise after the event. Rather more interestingly, it shows what goes into being wise after the event, what being wise after the event consists of perceptually. And as Goodman points out, once you have circumstantial, independent evidence to the effect that groups A, B, and C are Van Meegerens, whereas the groups from D to M are in fact true examples of Vermeer, you can see it. Once you have a perceptual incentive to see the difference, the difference is glaringly apparent.

Now, this is related to something the great Harvard taxonomist and systematist Ernst Mayr pointed out. During the 1930s, fireflies in the Caribbean comprised no more than about four or five different species, based on morphological grounds. After World War II, new, electronic methods of recording the flash frequencies of fireflies showed that on flash-frequency criteria there were at least 14 or 15 different species. When the flies were caught and sorted into enameled trays according to their flash frequencies, morphological differences which had previously passed unnoticed suddenly showed that there were as many species on morphological criteria as there were on flash-frequency criteria. In other words, there was a perceptual incentive to *look* for differences that had previously passed unnoticed.

Something very similar happened with Gilbert White, the author of *The Natural History of Selborne*. Two types of hedge bird, what we now know as the meadow warbler and the pippit, had previously been regarded as members of one species. When White observed them more closely and noticed that there were two song patterns, it became apparent that what had been thought to be one species actually split morphologically into two. And that's exactly what was happening, I think, in the case of the Vermeers and Van Meegerens.

Now, this is a roundabout route to asking the deeper question: Why is it that now, more than 50 years later, anyone—not just an art historical expert, but *anyone*—going down into the basement of the Rijksmuseum and looking at Van Meegeren's Vermeer forgeries will wonder: How was anyone ever taken in by it? Again, this is not simply being wise after the event. Something

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The truncated Belvedere torso (above, left) in the Vatican Museum doesn't look today much like what its creator sculpted 2,000 years ago, but we're accustomed to thinking it's beautiful the way it is. Around the turn of the 20th century, Auguste Rodin, inspired by the incompleteness of such statue fragments from the ancient world, intentionally created a number of headless, armless, legless torsos like the bronze *Marsyas* (*Large Torso of a Man*) (above, right). (Gift of the B. Gerald Cantor Art Foundation. Reproduced by permission of the Los Angeles County Museum of Art.)

much more fundamental is happening than what Goodman pointed out on the first occasion when the distinction was made. Why is it that people now, 50 years later, say, "These are quite clearly not Vermeers." They may not know that they're by someone trivial like Van Meegeren, but they know that they're not Vermeers. It is clearly apparent by 1990 that they're not Vermeers, and the reason is simply this: that what people thought Vermeer exemplified and what in Vermeer a forger thought was worth copying in 1930 were completely different from what people thought worth copying, even to the point of being indistinguishable, in 1990. So that even though the name of the game in forgery is indistinguishability, the forgeries become distinguishable with the passage of time, because time brings in a different view of what you think you are copying and what you are doing *by* copying something. In the act of copying something, you are introducing a perceptual bias, some sort of idea of what you think is exemplified by the prototype, what you think is valuable in it, what is worth reproducing in it.

If that's the case with something like an autographic work, think how much truer it is when it comes to something Goodman has described as an allographic work, one that doesn't depend on reproducing an artifact but on simply obeying a series of verbal instructions with a view to a performance. After all, there is a sense in which *Hamlet* doesn't exist between its successive performances. It exists in the form of these genetic instructions, but they're fixed in amber in the library. They can be read by people, but *Hamlet* itself in some plenary form doesn't exist until it is brought into intermittent and successive realization in performance. But the problem is: How do you obey the genetic instructions? What do you think the genetic instructions exemplify? This deep interpretive problem arises with the passage of time. But even if you take the instructions and reproduce every single word of *Hamlet*, why is it that successive versions of the play look so different? Because what we think the text exemplifies, what we think it is an instance of, will vary with the passage of time.

This happens with anything that we inherit from the distant past. All of these works are in their afterlives. We value them for reasons totally different from the reasons they were valued by their maker, and also for reasons very different from the reasons they were valued by their audiences at the time they were first seen. Think of the Belvedere torso in the Vatican Museum in Rome—this armless, legless object, this strange, luminous, twisted torso, which has no limbs at all. We know perfectly well that the author of that work would be extremely distressed to find it in that form. He would have to say, "Well, you should have seen it when it had its arms. I'm very disappointed to think that you're exhibiting this mutilated version. It scarcely counts as an instance of my work." And yet, in some odd way, it is in that mutilated version that we cherish it, so much so that we would be deeply distressed, I suspect, if by some sort of radiocarbon dating method we could find the original arms and put them back on again. There would be a sense that in some way it had been violated just as much as was the Michelangelo *Pieta* in the Vatican with its nose knocked off. The restoration is often seen by us as almost as much a destruction as a mutilation, and that is because it has entered our lives in the form that it has. Rodin, inspired by such mutilation, made some of his statues limbless or headless or armless because he got excited by the very form in which the work actually entered its afterlife.

I think any responsible director in the theater, sort of like a plant breeder, takes these strange genetic instructions from the distant past and makes them into something intriguing and interesting to an audience in the late 20th century, makes them recognizable. I don't want to use the word "relevant" because I think relevance actually means that it always has to address current problems. I don't think things from the past are made interesting by torturing them until they deliver some sort of confidence about our situation. This is an example of what T. S. Eliot called "the overvaluing of our own times," as if the works from the past exist in a sort of probationary relationship to our own times, as if they are interesting only insofar as they can address our problems. That's going to the other extreme. I think there must be some way in which we actually treat them as alien objects, as something coming from something else, from elsewhen, from elsewhere, but nevertheless, unavoidably, they have to be treated as if they're going to interest us in some way without necessarily addressing our current interests. Not every version of a Verdi opera has to be set, as so many German colleagues of mine do it, in a concentration camp in order to be interesting to us. But there *are* ways of reconstructing and, God forbid, deconstructing them—one of the hideous new trends in the theater these days. It's as if the genetic instructions are bequeathed to the modern director, who then does a lot of genetic engineering on the instructions themselves and actually transplants things and makes them mean something totally different from what they might have meant at the time. But I think there is a generic range of meaning that things might have, and if you go beyond that, you make a shambles of the work.

As I near my retirement from the theater, I find myself confronted by this very peculiar problem of dealing with works which come from a long time ago. One of the paradoxes of modernity is that it is characterized by extraordinary archival obsession with its inheritance. In 1700 no one would have expected to see a performance of a play or an opera which came from a hundred years earlier. Monteverdi was not performed for 300 years. He went into some sort of peculiar aesthetic hibernation. The idea of performing Monteverdi 25 years after his death would have been completely inconceivable, just as it would have been inconceivable to have performed something from 100 years earlier. Why is it that we are so fascinated with retrieving these works from the past, and why is it possible to go to a concert hall or an opera house and see works from three successive centuries in the same evening sometimes? You can get a work by Monteverdi and a work by Schoenberg performed in the same evening.

But a culture so energetically retentive and so eager to bring stuff back from the distant past makes problems for directors, producers, and audiences. I think the audience has made the problem even harder for itself by insisting on the idea that there is a standard phenotype which must be preserved at all costs. In very big opera houses, such as the Metropolitan Opera in New York, where I've worked several times, audiences are deeply disturbed if they see a "classic," as they call it, transposed in some way—if they don't see lavish scenery, if they don't see what they think was the original phenotype on the stage. They have every reason to think that it was the original phenotype because they don't know what the original 19th-century version of Verdi looked like. I suspect they would probably be horrified by what went on in the 19th century. What happens is that modern audiences have another sort of psychological process going on not unlike Konrad Lorenz's imprinting of geese. What the audience thinks is the orthodox performance turns out merely to be the performance by which they were "imprinted" the first time they were exposed to it. In exactly the same way as you can get a greylag goose to court a wastepaper basket (if that's the first thing it's exposed to, it will go on courting a wastepaper basket in exactly the same way), modern audiences will go on courting the operatic equivalent of wastepaper baskets in the form of a prototype of the first time they saw *Il Trovatore*. If it departs from that, they think it's departing from orthodoxy. It's not. It's departing from what they were imprinted by, and the difference between that imprinting experience and the inaugural performance is probably very profound. If you were to compare the version they were imprinted by and found satisfactory, it would probably bear a very marginal relationship to what they think was the inaugural one. □

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Miller ended his lecture here to take questions from the audience, for which, given the wide-ranging answers, there was time for only two. The first asked whether the loss of meaning in Shakespeare's language between his day and our own might require translation. While Miller admitted that there are patches of obscurity in some Shakespearian passages, he was sure that good acting (and good directing, of course) can get the meaning across. He expressed some worry that, as a reluctance to read spreads, the past might become irrelevant, so that you get "this shrill demand to make the play into something in our own times." He mused about whether works of art wear out, whether they might cease to be recognizable at all, as if they came from Mars. "But as long as we keep breeding and have mothers and fathers and brothers and sisters and the sorts of rivalries that happen between siblings, I think we will understand everything about Shakespeare because that's what it's all about."

The second question, about changes in acting styles in Shakespearian theater, sent Miller off on a riff that took him from the actors' gestures in the first night of Twelfth Night *(which would be "illegible" to us) to the intricate meanings of the Virgin's hand gestures in 14th- and 15th-century Italian paintings of the Annunciation—to the way that modern gestures, like the high-five and baseball caps worn backwards, are spread, which is not akin, he insisted, to an epidemic ("a sort of playful AIDS"), nor spread "as described by some of the more enthusiastic and fundamentalist Darwinians by this idiotic notion called the meme." They spread because they mean something to those who adopt them, Miller concluded.*

As David Goodstein cut off questions and wished members of the audience a safe drive home, he urged them: "Let's have no experiments in perception on the way home. Look through the windshield, not at it."

Terry Cole 1931–1999

Terry Cole (PhD '58), senior faculty associate in chemistry and chemical engineering at Caltech and for nearly two decades chief technologist at JPL, died on August 20 at age 68. Born March 28, 1931, in Albion, New York, Cole earned a BS in chemistry from the University of Minnesota in 1954 before coming to Caltech for his doctorate. He stayed as a postdoc before taking a job at Ford Motor Company, where he held a variety of research and management positions from 1959 to 1980. He came to Caltech as a Sherman Fairchild Distinguished Scholar for nine months in 1976, returning for good as a research associate in chemistry in 1980. He was also appointed JPL's chief technologist that year, and retired from that post in 1998.

With one foot at Caltech and one at JPL, Cole was a vital conduit between the two institutions. Says JPL Chief Scientist Moustafa Chahine, "He had a deep, insider's knowledge of germinating ideas on campus and at JPL, and he knew how to put them together. This has left a void we are still trying to fill. He knew so much about so many things. He was always up to date, even after he retired. And he appreciated that science, which is Caltech's strength, and technology, which is JPL's strength, work hand-in-hand." Says Carolyn Merkel, director of Caltech's SURF (Summer Undergraduate Research Fellowship) program, in which Cole was deeply involved, "Terry had a knack for identifying people's interests and needs, and then putting together people who had problems or opportunities in common. And, often, something good would happen." Fred Shair, who founded the SURF program, offered this thumbnail portrait. "Terry was truly a Renaissance person. His love for music spanned the great jazz of Jelly Roll Morton to the classics. He could have made a living as a photographer—he was an artist. But unlike most artists, he was a virtuoso of the scientific fundamentals that explain how the beautiful patterns of nature emerge."

Cole's energy and enthusiasm were legendary. "He never walked into the SURF office—he always bounded in," Merkel recalls. With this verve came a gift for salesmanship. "He had this great ability to paint a verbal picture, to make you see his vision," says Merkel. Recalls Lew Allen, director of JPL from 1982 to 1991, "He would pop into my office and tell me about all these developments down on campus that he thought would be useful for space. He was very engaging and amusing, and he could get me excited about the things he saw coming along. He made it fun.

"For example," Allen continued, "NASA offered to construct us a building for microelectronic fabrication. I was dubious, but Terry convinced me that JPL had the capabilities to get into that field, if we made use of the expertise of people down on campus. And he was right." But getting the Center for Space Microelectronics Technology (CSMT) built was only the beginning—NASA was willing to fund its construction, but not its operation. Cole and Carl Kukkonen, whom Cole had recruited from Ford, had to go out and line up sponsors to use the facility in order to keep its doors open. Since its founding in 1987, it has provided key technologies used on Pathfinder and the rest of the new generation of smaller, faster, cheaper spacecraft, and in 1992, CSMT earned Cole NASA's Exceptional Service Award. Says Allen, "His advocacy greatly contributed to the strong technological position that JPL is in now."

Cole was also instrumental in getting JPL its first supercomputer. "JPL had never had a supercomputer," Allen explains, "because the project managers liked having their own smaller computers. Terry saw the benefits to be had from a larger machine the Lab and campus could use, but it was a challenge to fund, as it was too big to come from any individual budget." So Cole and Kukkonen talked it up, and arranged the backing—in essence, becoming time-share salesmen. Supercomputer use in image processing and mission design is now commonplace, says Chahine. "He took us from being a small-computer facility to supercomputers being an integral part of JPL. He changed the mindset." Today, the JPL Supercomputer Project and Caltech's Center for Advanced Computational Research share some of the fastest, most advanced machines in the world.

But Cole's greatest legacy may be the SURF program. Founded in 1979, SURF places students in the labs of participating faculty members for a summer of hands-on work; what made the program unique was that the students wrote their own research proposals and, at summer's end, presented papers on their work. (These papers often go on to appear in scientific journals, providing many undergrads with their first professional publications.) Cole greatly expanded SURF's scope in 1983, when he opened the door for students to work at JPL. Says Merkel, "With his usual enthusiasm, Terry became SURF's advocate. We were a fledgling program, and few people were aware of what we were trying to do. Terry fired the imaginations of faculty and JPL staff who hadn't yet participated. He talked convincingly to administrators whose support we needed. He excelled at explaining technology to laymen, and he was great with donors. He was an outstanding emcee, enlivening any SURF event with stories and easy humor, and he was as comfortable talking about art and literature as he was about science and technology. He was a master of aphorism, succinctly stating SURF's philosophy: 'no intellectual bottle-washing.' He would remind donors and mentors alike that 'money is the sincerest form of commitment.'" In 1989, he became chair of the SURF Administrative Committee—a position he held for the rest of his life. Under his leadership, 1,525 students have SURFed, roughly a quarter of them at JPL. More than half of Caltech's undergrads now SURF for at least one summer, and the program has spawned many imitators elsewhere.

"Terry had a passion for helping young people build a better world," says Shair. This showed not only in the SURF program but at JPL, where he founded the Telescopes in Education program, in which a 24-inch telescope at the Mount Wilson Observatory is available over the Internet for use by K–12 students around the world.

Says Chahine, "Terry's first goal at JPL was developing our intellectual capabilities. He had the connections in industry—at Ford and elsewhere—and in the universities to get people to come to JPL who otherwise wouldn't have. He brought in lots of talented people, especially as postdocs." Many of these young scientists stayed to become lifelong friends.

"He was an advisor, mentor, and problem-solver to everybody who sought his help, from postdoc to senior scientist," says Chahine. Merkel agrees. "If you ever needed an idea, you could call Terry. It didn't matter what kind of an idea—a mentor for a student with a particular interest, a fund-raising event, or a keynote speaker for a conference."

Cole battled prostate cancer the way he did everything else, says Chahine—he threw himself into it. "He studied it and understood it. Several colleagues who also had it relied on him for help, information, and support; sometimes several people at the same time. His knowledge and advice were invaluable. He helped others through, even as he was struggling to keep afloat himself. They say, first you help yourself, then you help others. Terry didn't do that."

A memorial service was held at Caltech's Athenaeum on October 22. Memorial contributions can be made to the SURF program, care of Carolyn Merkel, Caltech mail code 139-74, Pasadena, CA 91125; or to the Prostate Cancer Research Fund at USC-Norris Hospital, 1441 Eastlake Ave., Room 8302, Los Angeles, CA 90033. □

Cole was an accomplished nature photographer.

Honors and Awards

Jacqueline Barton, the Hanisch Memorial Professor and professor of chemistry, has been elected a member of the American Philosophical Society "for her achievements in science." She has also received the 1999 G. M. Kosolapoff Award for Scientific Distinction from Auburn University.

Roger Blandford, the Tolman Professor of Theoretical Astrophysics, has received the Royal Astronomical Society's Eddington Medal for Theoretical Astronomy.

Professor of Literature, Emeritus, *Kent Clark*'s "influence on the lives of many generations of Caltech undergraduates" has been recognized through the establishment of the J. Kent Clark SURF Endowment, which will support one student in the humanities each summer, in perpetuity.

Mark Davis, the Schlinger Professor of Chemical Engineering, has won the American Institute of Chemical Engineers' 1999 Professional Progress Award.

Peter Dervan, the Bren Professor of Chemistry, has been selected by the Oregon, Portland and Puget Sound Sections of the American Chemical Society to receive the 1999 Linus Pauling Medal, which "recognizes

Honors and Awards (continued)

outstanding accomplishments in chemistry in the spirit of and in honor of Linus Pauling." In addition, Harvard University has chosen Dervan to be its 1999 Max Tishler Prize Lecturer.

Professor of Chemistry *Dennis Dougherty*, who is also executive officer for chemistry, has been elected a Fellow of the American Academy of Arts and Sciences.

The 1999 teaching awards of the Associated Students of Caltech (ASCIT) have gone to *Peter Goldreich*, the Dubridge Professor of Astrophysics and Planetary Physics; *Robert McEliece*, the Puckett Professor and Professor of Electrical Engineering; *Daniel Meiron*, professor of applied mathematics; *E. Sterl Phinney*, professor of theoretical astrophysics; and *Beena Khurana*, visiting assistant professor of psychology. Recipients of honorable mentions are *Marianne Bronner-Fraser*, professor of biology; *Kip Thorne*, the Feynman Professor of Theoretical Physics; *Sara Lippincott*, lecturer in creative writing; and *Michael Shumate*, instructor in applied physics.

Recipients of the 1999 Graduate Student Council teaching and mentoring awards are, for excellence in teaching, Professor of Applied Mechanics *Stephen Wiggins* and, for excellence in mentoring, Professor of Chemical Physics *Aron Kuppermann*.

Professor of Economics and Social Sciences *John Ledyard*, chair of the Division of Humanities and Social Sciences, has been elected a fellow of the American Academy of Arts and Sciences "in recognition of distinguished contributions to his profession."

Assistant Professor of Chemistry *Jonas Peters* has received the 1999 Camille and Henry Dreyfus New Faculty Award.

Kip Thorne, the Feynman Professor of Theoretical Physics, has been elected a member of the American Philosophical Society, and a foreign member of the Russian Academy of Sciences.

New Division Chair

David Tirrell

David Tirrell, the Ross McCollum-William H. Corcoran Professor and professor of chemistry and chemical engineering since 1998, has been named chair of the Division of Chemistry and Chemical Engineering, succeeding Peter Dervan, the Bren Professor of Chemistry.

Tirrell's research focuses on connections between materials science and the biological sciences. His specific interests include the preparation of new materials for application in biology and medicine and a better understanding of the ways in which materials are made in nature.

Before coming to Caltech, Tirrell was director of the National Science Foundation Materials Research Science and Engineering Center at the University of Massachusetts, where he was also the Barrett Professor of Polymer Science and Engineering. He earned a master's and Ph.D. in polymer science and engineering from the University of Massachusetts in 1976 and 1978, respectively. His bachelor's degree in chemistry (1974) is from MIT.

As *E&S* went to press, the Royal Swedish Academy of Sciences awarded Ahmed Zewail, the Pauling Professor of Chemical Physics and professor of physics, the Nobel Prize for chemistry. Zewail pioneered the field of femo chemistry, which uses ulrafast laser pulses to watch chemical reactions as they happen. Look for the full story in the next issue.

New Director for Alumni Association

Andrew (Andy) Shaindlin has been named executive director of Caltech's Alumni Association, succeeding Judy Amis, who retired last year.

Shaindlin comes to Caltech from the University of Michigan, where, since 1996, he served as director of alumni education and then senior director of alumni programs. He was responsible for directing one of the nation's largest alumni travel programs, overseeing the new Alumni Career Center, and administering the Alumni University education program.

Andy Shaindlin

From 1989 to 1996 Shaindlin served as associate director, and before that as assistant director, of alumni relations at Brown University where he had earned his BA in international relations in 1986. He also held various posts with the Princeton Review from 1987 to 1989, including director of the Princeton Review of Long Island.

His achievements include establishing two Internet discussion forums for alumni professionals, as well as publishing a number of articles

Returning the Favor

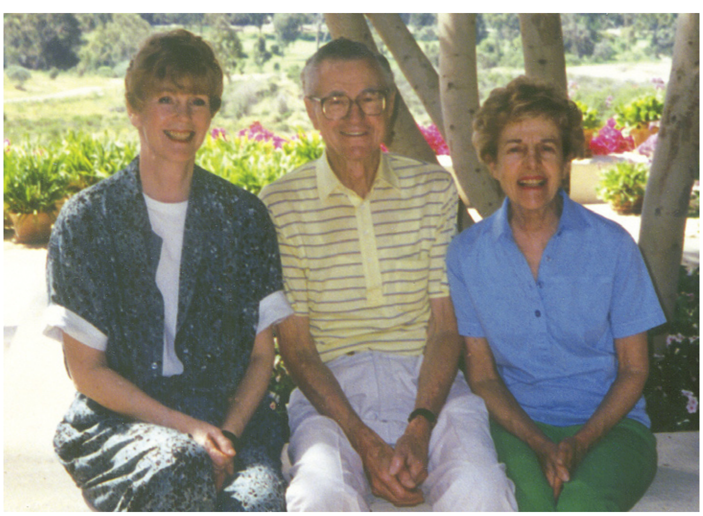
Above: Caltech's chapter of the American Society of Mechanical Engineers, circa 1931; Rea Axline is front and center. Left: Axline early in his career.

On June 23 Caltech received by wire transfer more than $60 million in cash and stock from the estate of Rea (BS '31ME) and Lela G. (Jackie) Axline, representing the initial distribution of what will amount to the largest single gift in the Institute's history. Additional distributions will be much smaller, but once completed the bequest will likely total close to $65 million. The Axlines provided in their trust that, after payment of a few specific bequests and expenses of the estate, Caltech was to receive one-half of the remaining assets, to be used as endowment to support student financial aid.

The bequest is reflective of Rea Axline's interest in his alma mater and, in particular, his sense of gratitude for the financial assistance provided to him by the Institute during his years as an undergraduate. Indeed, among the few important papers he kept all his life were the no-interest loan documents issued to him by the Institute, including a letter he received from Caltech in 1936 confirming repayment in full and thanking him for paying off the loans well before the due date. It is a little shocking (in these days of five-figure annual tuition bills) to discover that the loans he received during his two years at Caltech totaled a mere $160. Nonetheless, Rea's saving these papers all these years makes it apparent that even before he had the wherewithal to make such a wonderful bequest he was deeply appreciative of the loans and was committed to returning the favor. Another saved letter from Caltech, this from 1930, notified him that his loan had been approved and included a request that after graduation he consider making an annual gift of "$10, or as much more as you may feel able to give, so that other worthy students at that time may be helped as you are being helped now." Obviously Axline took this request to heart.

The Axlines' bequest is, to put it simply, a profound act of philanthropy.

Rea and Jackie Axline with their niece, Joan Eckart (left).



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