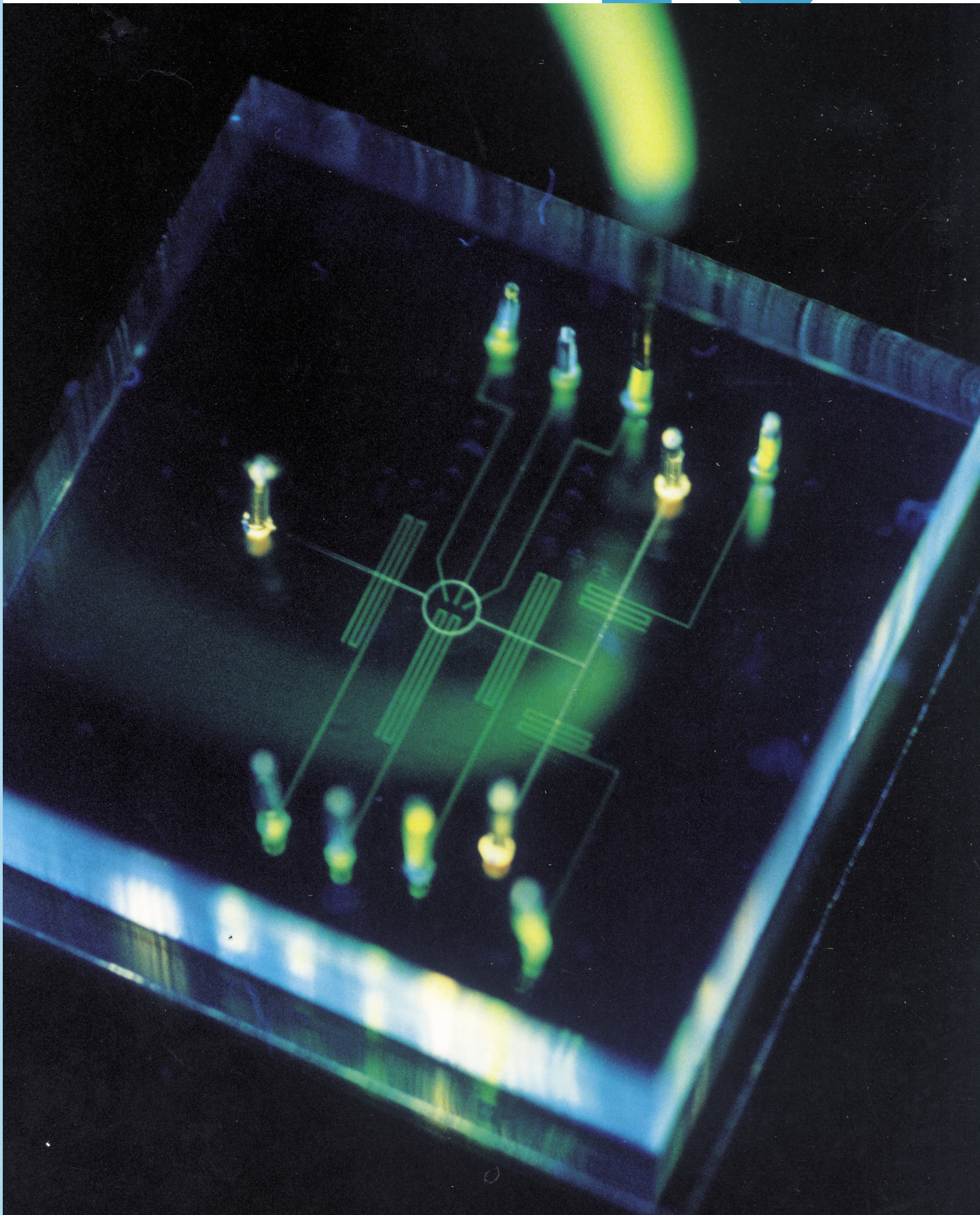
California Institute of Technology

E&S
Engineering and Science

Volume LXVI, Number 2,
2003



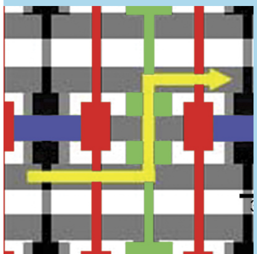
IN THIS ISSUE

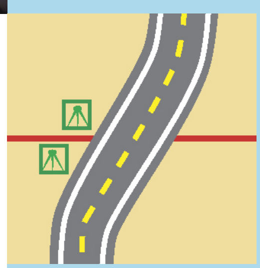
Once a year, Caltech geologists set up a GPS receiver in front of Yucca Mountain—the proposed nuclear-waste storage site in Nevada—and record the exact global coordinates. And every year, the site has moved a few more millimeters west-northwest, because this part of the North American tectonic plate is pulling away from the interior. Starting on page 26, you can read how geologists are beginning to understand the relationship between the incredibly slow, but steady, movement of tectonic plates, and the sudden, unpredictable, nature of earthquakes.

California Institute of Technology

ENGINEERING & SCIENCE

Volume LXVI, Number 2, 2003





On the cover: The glowing lines in this photo are channels roughly 10 times the diameter of a red blood cell. The postage-stamp-sized silicone (not silicon!) chip in which they are embedded was custom-made to run the polymerase chain reaction, which allows large quantities of DNA to be made from a single molecule in, say, a blood sample. For more on how tiny, leakproof valves and pumps of flexible rubber could one day put an entire biology laboratory on a chip, see the story beginning on page 8. Chip courtesy of Jian Liu.

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: Cover, 2, 5, 7, 10, 11, 14, 16, 18-20, 22-25, 44 – Bob Paz; 3, 14 – Doug Cummings; 4 – Libby Mayo/ Brian Leigh; 8 – Sebastian Maerkl; 9, 10 – Fluidigm; 12 – Doug Smith; 13 – Carl Hansen; 15 – Axel Scherer; 21 – Caltech Archives; 27 – USGS; 28, 29 – Tanya Atwater; 28 – Joann Stock; 30, 31 – Brad Aagaard, Tom Heaton; 30 – Shijie Zhong, Mike Gurnis; 31 – Puget Sound LIDAR Consortium; 32 – Jim McCalpin, GEO-HAZ Consulting; 34 – Kerry Sieh; 38, 39 – NASA

Visit Caltech on the Web at **http://www.caltech.edu**

The Class of 2003 Commences

Most of the class of '03 convenes (above) for a group photo before processing down the Court of Man to receive their diplomas and to hear noted biologist Harold Varmus (right) express his hope that society would treat them well and that science would remain an "exhilarating experience" for them.

At the 109th Caltech Commencement on June 13, 242 students graduated with their BS degrees, 111 received MS degrees, and 137 earned PhDs. And they all heard Harold Varmus urge them to reflect on how society serves science and to maintain a sense of joy and awe in doing science. Varmus, president and chief executive officer of Memorial Sloan-Kettering Cancer Center in New York, and former director of the National Institutes of Health, won the 1989 Nobel Prize in physiology or medicine for his studies of the genetic basis of cancer.

Varmus had provided all the graduates with a copy of Vittore Carpaccio's 1502–04 painting of St. Augustine in his study, surrounded by the tools of his trade (books, manuscripts, laboratory equipment) as they would have appeared during the Renaissance, as well as religious objects signifying the source of his support: the Church, which was "his NIH and his Caltech." What the Church expected in return for its generosity, said Varmus, was "apparently a mixture of intense philosophical thought, broad curiosity about the arts and sciences, and possibly a bit of practical invention."

He compared this mutually beneficial situation with the present day, 500 years after the painting, when the government rather than the Church is the biggest benefactor of science. We are also "fortunate to live in a culture that values scientific inquiry highly," when "our nation's financial investments in science are large, and the political support is generally strong."

But he reminded the audience that a century after Carpaccio's painting, the Church branded Galileo a heretic for the freedom of thought celebrated in the picture. There are economic, political, and social currents today, he said, that suggest that we also are in for a change of climate. "In this environment, society's expectations for science can shift to short-range necessities at the expense of unfettered inquiry into basic truths," Varmus warned. He hoped these concerns would "prove to be short-term and even exaggerated."

Switching to a topic more in keeping with the festive occasion, Varmus spoke of the importance of science remaining an "exhilarating experience, not just a grim duty." He offered two illustrations: Canadian astronomer Rebecca Elson and "internationally revered" biologist Ira Herskowitz, BS '67. Elson wrote poems and essays about her delight and thrill in spending "my days inside a tent with such a dazzling roof," published after her death at 39 in a collection called *A Responsibility to Awe.*

Herskowitz, Varmus's friend and colleague, who died in May at 56, "never lost his simple sense of joy, his 'responsibility to awe,' about a beautiful experiment," said Varmus. "He viewed science as an aesthetic experience."

Such people "illustrate the state of science in our society," Varmus told the graduates, "just as Carpaccio's vision of St. Augustine reveals the condition of scholarship in the early Renaissance. Science and society—a relationship that is built on mutual dependencies and inherently fragile—yet together capable of remarkable achievements: an understanding of life, our planet, our universe, and even ourselves." ☐ —*JD*

A Modest Proposal

Dave Stevenson has spent his career working on "swing-by" missions to the other planets. Now he has a modest proposal he'd like to swing by some government agency with a few billion dollars in available funding.

According to Stevenson's calculations, it should be possible to send a probe all the way to Earth's core by combining several proven technologies with a few well-grounded scientific assumptions about the workings of the planet. The probe would sink straight to the core in an envelope of molten iron, sending back temperature readings, compositional information, and other data along the way.

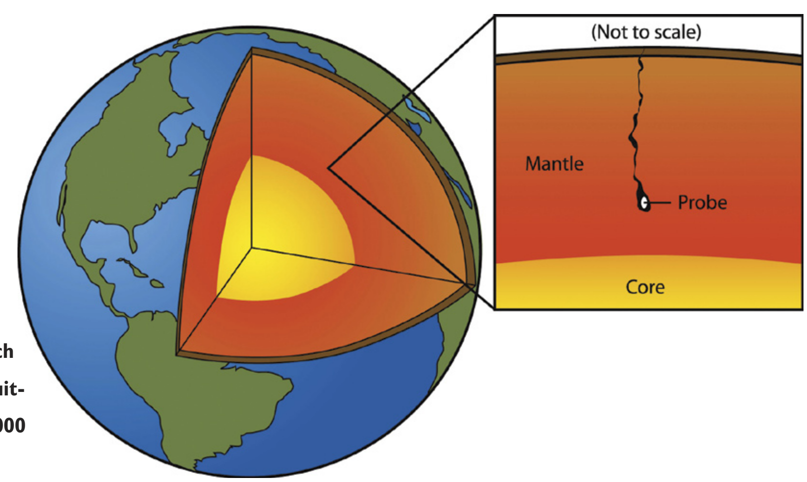
"We've spent more than $10 billion in unmanned missions to the planets," says Stevenson, the Van Osdol Professor of Planetary Science, "but we've only been down about 10 kilometers into our own planet."

The benefits to science would be significant, Stevenson says, because so little has been directly observed about the inner workings of the planet. Scientists do not know, for example, the exact composition or even the temperature of the core, and what they do know is based on inferences about seismic data accumulated during earthquakes.

Stevenson says his proposal should be attractive to the scientific community because it is of the same scale, pricewise, as planetary exploration. To date, NASA has flown unmanned missions past all the planets except Pluto (if indeed Pluto is a planet at all), has made a few highly successful soft landings on Mars, has probed the clouds of Jupiter, is getting ready to probe the atmosphere of Titan, and has sent four spacecraft into interstellar space. Sending something into Earth's core, Stevenson believes, will have comparable payoffs in the quest for knowledge.

"When we fly to other worlds, we are often surprised by what we find, and I think the same will be the case if we go down."

Stevenson's plan calls for a crack to be opened in Earth's surface, perhaps with some sort of explosion—probably a nuclear bomb. According to



Stevenson's proposal to visit Earth's interior does not include humans—unlike the recent movie *The Core.* Instead, he thinks it might be possible to open up a relatively narrow crack and pour down molten iron, which would carry along a grapefruit-sized probe while sinking 3,000 kilometers to the core.

his figures, the crack will need to be several hundred meters in length and depth, and about 30 centimeters wide, to accommodate a volume of about 100 thousand to several million tons of molten iron.

The instant the crack opens, the entire volume of iron will be dropped in, completely filling the open space. Through the sheer force of its weight, the iron will create a continuing crack that will open all the way to the planet's core 3,000 kilometers below. Anything on a smaller scale may not work; anything larger will be even more expensive, so Stevenson thinks a crack of those dimensions is about right.

"Once you set that condition up, the crack is self-perpetuating," he explains. "It's fundamentally different from drilling, where it gets harder and harder—and eventually futile—the farther you go down."

The iron will continue to fall due to gravity because it is about twice the density of the surrounding material. Riding along in the mass of liquid iron will be one or more probes made of a material robust enough to withstand the heat and pressure. The probe will perhaps be the size of a grapefruit but definitely small enough to ride easily inside the 30-centimeter crack without getting wedged.

Inside the probe will be instrumentation for data collection, which will be relayed through low-intensity mechanical waves of some sort—probably through deformations of the ball itself to send out a sort of "Morse code" of data. Because radio waves cannot propagate through Earth, this is the only way to get the data transferred.

The probe will likely operate with about 10 watts of power, and it may even be possible to replenish its energy and dispense with an on-board battery by harnessing mechanical energy from the force of the fall, just as electricity can be generated from falling water.

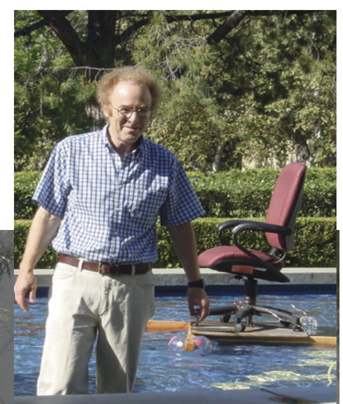
Such a low power rating will not make it possible to generate very strong shock waves for data transmission, but strong waves may not be necessary. In fact, Stevenson further suggests that the Laser Interferometer Gravitational-Wave Observatory (LIGO) might be recalibrated in its downtime to track the falling ball.

Based on the rate the molten iron would fall due to gravity, the ball would move downward into the planet at roughly human running pace (about 10 miles per hour), meaning that the entire mission would last a few weeks.

All this may sound to some like science fiction, but Stevenson says each of the principles involved is based on sound knowledge of crack propagation, fluid dynamics, mechanical-wave propagation, and "stress states." If these things didn't already work in nature, we would have no volcanoes and poorly performing bathroom plumbing, but little to fear from a pebble shattering our windshields.

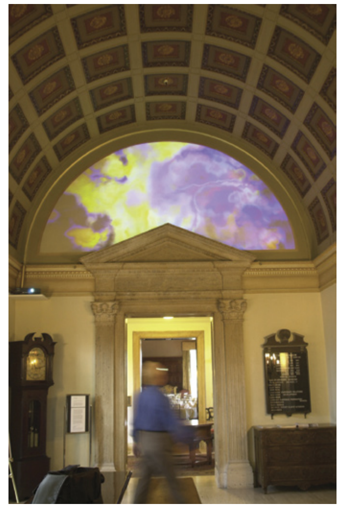
"The biggest question is how to initially open the crack," says Stevenson. "Also, there's the technological challenge of having a probe that actually does what it's supposed to do."

Stevenson floated his idea in the journal *Nature* in May under the title "A Modest Proposal," taken from Jonathan Swift's famous essay. "My proposal is not as outrageous as suggesting one should eat his own children, but still combines a serious proposal with some levity," Stevenson says. "Ninety-five percent of the scientists who read the article may laugh at an enjoyable read, but if the other five percent seriously consider the goal of probing Earth's core, then I'll be happy." □ —*RT*



When he arrived at work on July 2, Bruce Brunschwig (inset) found that his entire office had been launched on floats in the "gene pool" (so called because the tiles on its bottom form a DNA double helix). Brian Leigh, Libby Mayo, and other grad students in the Beckman Institute carried out the early-morning move to welcome Brunschwig to his new post as head of the Molecular Materials Research Center. Nothing got wet—except Brunschwig, who enjoyed the stunt immensely.

Continuously changing images of exploding fireballs decorate a tympanum of the Athenaeum lobby as part of *NEURO*, an exhibition cosponsored by Caltech and Art Center College of Design. The exhibition featured six artists who created their works in collaboration with Caltech scientists. This contribution by media artist Jennifer Steinkamp, entitled *Einstein's Dilemma*, symbolizes the impact that new scientific knowledge has on human culture.



H_2 Uh, Oh

According to conventional wisdom, hydrogen-fueled cars are environmentally friendly because they emit only water vapor—a naturally abundant atmospheric gas [see *E&S*, No. 1, 2003]. But leakage of the hydrogen gas that can fuel such cars could cause problems for the upper atmosphere, new research shows.

In an article that appeared in a June issue of the journal *Science*, Caltech researchers reported that the leaked hydrogen gas that would inevitably result from a hydrogen economy, if it accumulates, could indirectly cause as much as a 10 percent decrease in atmospheric ozone. The researchers are Tracey Tromp, physics research scientist; John Eiler, assistant professor of geochemistry; Yuk Yung, professor of planetary science; Run-Lie Shia, PhD '86, planetary science research scientist; and Mark Allen, PhD '76, Jet Propulsion Laboratory scientist.

If hydrogen were to replace fossil fuel entirely, the researchers estimate that 60 to 120 trillion grams of hydrogen would be released each year into the atmosphere, assuming a 10 to 20 percent loss rate due to leakage. This is four to eight times as much hydrogen as is currently released into the atmosphere by human activity, and would result in a doubling or tripling of inputs to the atmosphere from all sources, natural or human.

Because molecular hydrogen freely moves up and mixes with stratospheric air, the result would be the creation of additional water at high altitudes and, consequently, an increased dampening of the stratosphere. This in turn would result in a cooling of the lower stratosphere and a disturbance of ozone chemistry, which depends on a chain of chemical reactions involving hydrochloric acid and chlorine nitrate on water ice.

The estimates of potential damage to stratospheric ozone levels are based on an atmospheric modeling program that tests the various scenarios that might result, depending on how much hydrogen ends up in the stratosphere from all sources, both natural and anthropogenic.

Ideally, a hydrogen fuel-cell vehicle has no environmental impact. Energy is produced by combining hydrogen with oxygen pulled from the atmosphere, and the tailpipe emission is water. The hydrogen fuel could come from a number of sources (Iceland recently started pulling it out of the ground). Nuclear power could be used to generate the electricity needed to split water, and in principle, the electricity needed could also be derived from renewable sources such as solar or wind power.

By comparison, the internal combustion engine uses fossil fuels and produces many pollutants, including soot, noxious nitrogen and sulfur gases, and the "greenhouse gas" carbon dioxide. While a hydrogen fuel-cell economy would almost certainly improve urban air quality, it has potential unexpected consequences due to the inevitable leakage of hydrogen from cars and hydrogen production facilities, and during the transportation of the fuel.

Uncertainty remains about the effects on the atmosphere because scientists still have a limited understanding of the hydrogen cycle. At present, it seems likely such emissions could accumulate in the air. Such a build-up would have several consequences, chief of which would be a moistening and cooling of the upper atmosphere and, indirectly, destruction of ozone. In this respect, hydrogen would be similar to the chlorofluorocarbons (once the standard substance used for air conditioning and refrigeration), which were intended to be contained within their devices, but which in practice leaked into the atmosphere and attacked the stratospheric ozone layer.

The authors of the *Science* article say that the current situation is unique in that society has the opportunity to understand the potential environmental impact well ahead of the growth of a hydrogen economy. This contrasts with the cases of atmospheric carbon dioxide, methyl bromide, CFCs, and lead, all of which were released into the environment by humans long before their consequences were understood.

"We have an unprecedented opportunity this time to understand what we're getting into before we even switch to the new technology," says Tromp, the lead author. "It won't be like the case with the internal-combustion engine, when we started learning the effects of carbon dioxide decades later."

The question of whether or not hydrogen is bad for the environment hinges on whether the planet has the ability to consume excess anthropogenic hydrogen, explains Eiler. "This man-made hydrogen will either be absorbed in the soil—a process that is still poorly understood but likely free of environmental consequences—or react with other compounds in the atmosphere.

"The balance of these two processes will be key to the outcome," says Eiler. "If soils dominate, a hydrogen economy might have little effect on the environment. But if the atmosphere is the big player, the stratospheric cooling and destruction of ozone modeled in this *Science* paper are more likely to occur.

"Determining which of these two processes dominates should be a solvable problem," states Eiler, whose research group is currently exploring the natural budget of hydrogen using new isotopic techniques.

"Understanding the effects of hydrogen on the environment now should help direct the technologies that will be the basis of a hydrogen economy," Tromp adds. "If hydrogen emissions present an environmental hazard, then recognizing that hazard now can help guide investments in technologies to favor designs that minimize leakage. On the other hand, if hydrogen is shown to be environmentally friendly in every respect, then designers could pursue the most cost-effective technologies and potentially save billions in needless safeguards."

If hydrogen indeed turns out to be bad for the ozone layer, should the transition to hydrogen-fueled cars be abandoned? Not necessarily, Tromp and Eiler claim.

"If it's the best way to provide a new energy source for our needs, then we can, and probably should, do it," Tromp says. □ *—RT*

Caltech is now the owner of a Pasadena landmark: the 13-acre, multi-structure St. Luke Medical Center, four miles northeast of campus, which the Institute plans, over time, to convert into a state-of-the-art research facility. The site, provisionally dubbed (CIT)^2 for Caltech Center for Innovative Technologies, will give the Institute an opportunity to expand current research programs and to contemplate new avenues for research. The purchase was consummated July 1 with the Tenet Healthcare Corporation, which had bought the facility in 1997 and closed it last year. Originally built in 1933 by the Sisters of St. Joseph of Orange (to whom the cross atop the dome will be returned), it was one of the first hospitals in the San Gabriel Valley.

FLEE OR FREEZE

In most old-fashioned black-and-white horror flicks, it always seems there's some hapless hero or heroine who gets caught up in a life-threatening situation. Instead of making the obvious choice—to run like hell—he/she freezes in place. That decision, alas, leads to their ultimate demise.

While their fate was determined by bad scriptwriting, scientists already know that in real life, environment and experience influence defensive behaviors. Less understood are the neural circuits that determine such decisions. Now, Caltech researchers have developed an experimental model using mice that can map and manipulate the neural circuits involved in such innate behaviors as fear.

Raymond Mongeau, Gabriel A. Miller, BS '99, Elizabeth Chiang, BS '01, and David J. Anderson, in work performed at Caltech, manipulated either a flight or freeze reaction in mice through the use of an ultrasonic auditory stimulus, and further, were able to alter the mouse's behavior by making simple changes in the animal's environment. They also found that fleeing and freezing are negatively correlated, suggesting that a kind of competition exists between these alternative defensive motor responses. Finally, they have begun to map the potential circuitry in the brain that controls this competition.

"Fear and anxiety are important emotions, especially in this day and age," says Anderson, professor of biology at Caltech and an investigator with the Howard Hughes Medical Institute. "We know a lot about how the brain processes fear that is learned, but much less is known about innate or unlearned fear. Our results open the way to better understanding how the brain processes innately fearful stimuli, and how and where anxiety affects the brain to influence behavior."

Using the ultrasonic cue, the researchers were able to predict and manipulate the animal's reaction to a fearful situation. They found that mice exposed to the ultrasonic stimulus in their home cage (a familiar environment) predominantly displayed a flight response. Those placed in a new cage (an unfamiliar environment) or treated with foot shocks the previous day, primarily displayed freezing and less flight.

Anderson noted that in previous fear "conditioning" experiments, where mice learned to fear a neutral tone associated with a foot shock, the animals showed only freezing behavior and never flight, even though in the wild, flight is a normal and important fear response to predators. This suggests that the ultrasonic stimulus used by Anderson and colleagues is tapping into brain circuits that mediate natural, or innate, fear responses that include flight as well as freezing.

What causes the shift from flight to freezing behavior? Probably high anxiety and stress, say the authors, caused by an unfamiliar environment or the foot shocks. The researchers suggest that freezing requires a higher threshold level of anticipatory fear (the heroine inside a dark, spooky house) before it can be elicited by the ultrasound.

Most brain researchers believe the brain uses a hierarchy of neural systems to determine which defensive behaviors, like flight or freezing, to use. These range from an evolutionary older neural system that generates "quick and dirty" defensive strategies, to more evolved systems that produce slower but more sophisticated reactions. These systems are known to interact, but the neural mechanisms that decide which response wins out are not understood.

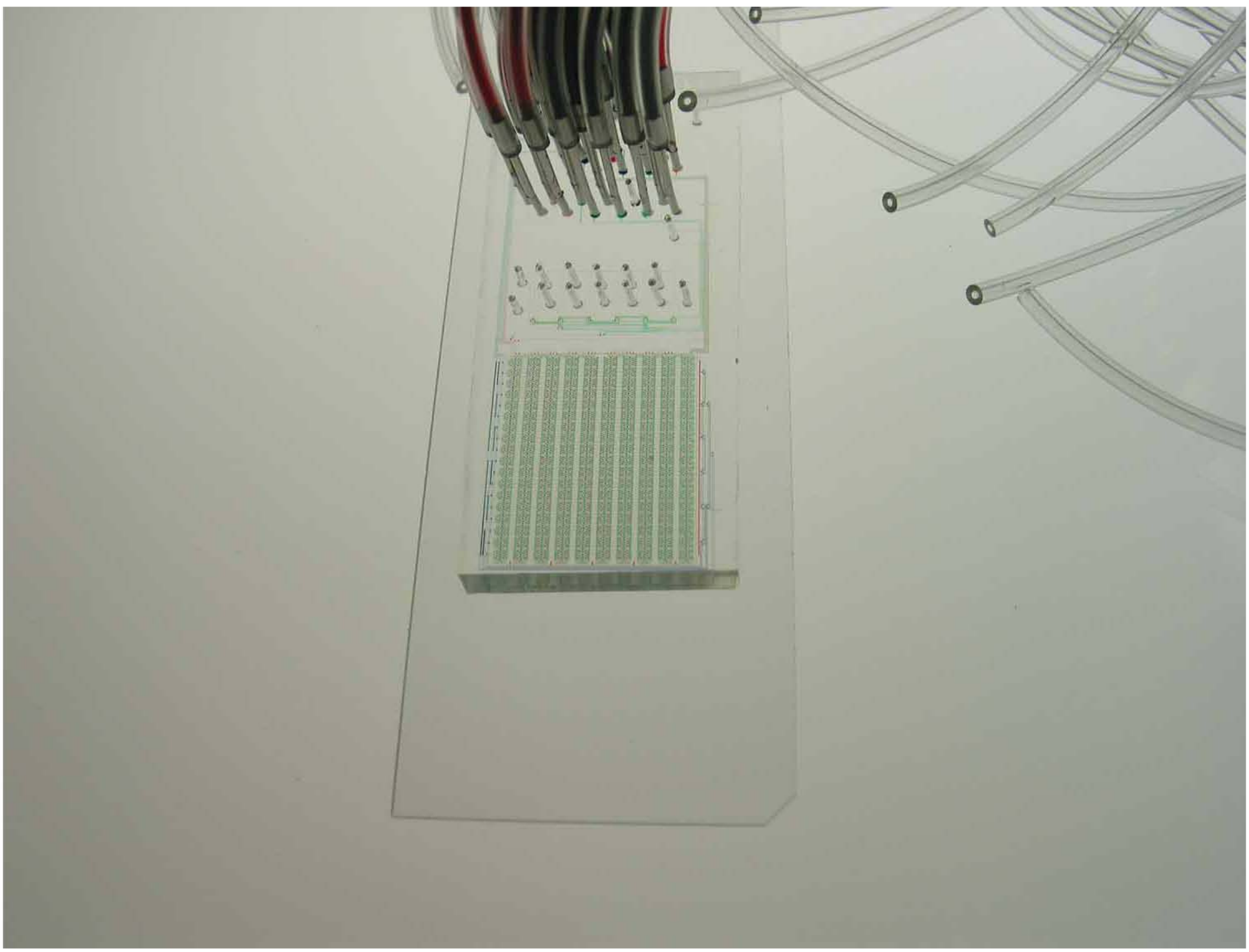
One of the goals of the investigators' work was to map the brain regions that control the behaviors triggered by the fear stimulus, to observe whether any change in brain activity correlated with the different defensive behaviors. They achieved this, all the way down to the resolution of a single neuron, by mapping the expression pattern of the c-FOS gene, a so-called "immediate early gene" that is turned on when neurons are excited. The switching on of the c-FOS gene can therefore be used as an indication of neuronal activation.

A map of the c-FOS expression patterns during flight vs. freezing revealed that mice displaying freezing behavior had neural activity in different regions of the brain than those that fled. Some of these regions were previously known to inhibit each other, providing a possible explanation for the apparent competition between flight and freezing observed in the intact animal.

Anderson notes that more work needs to be done to pin down where and how anxiety modifies defensive behavior. "This system may also provide a useful model for understanding the neural substrates of human fear disorders, like panic and anxiety," says Anderson, "as well as provide a model for developing drugs to treat them." □ —*MW*

More than 150 participants from across the country met June 27–28 at Caltech for "Women in Astronomy II," cosponsored by the American Astronomical Society as a follow-up to the first meeting in 1992, which endorsed a broad range of goals calling for improvements in opportunities and working environments for women in the field. Although gender equity in astronomy remains a problem, the numbers are improving, it was announced at the conference. Women now earn 22 percent of PhDs in astronomy and hold 14 percent of faculty positions. Most hopeful were the numbers for younger astronomers: in the 23–28 age bracket, nearly 40 percent were women, as well as almost 60 percent of those between 21 and 23.

You stick the pins in, and—thhhp!—the rubber just seals itself to them. This is a huge advantage, says Unger. "Imagine trying to epoxy a glass capillary the size of a grasshopper's shin onto a hole the same size—that's what people used to have to do."



Rubber Layered Micropumpers

by Douglas L. Smith

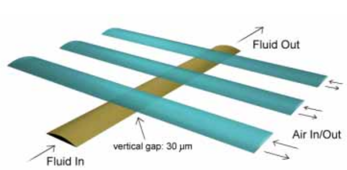
Left: The very latest in protein-chemistry chips can handle 720 samples at once.

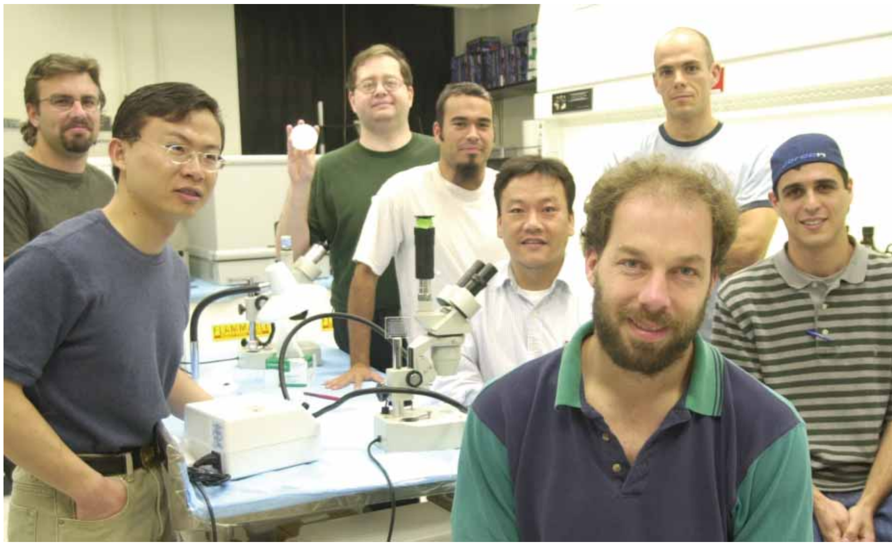
When you see the headlines—"Fat Gene" Found! DNA Solves Decades-Old Murder! Biotech Miracle Drug Announced!—you might think that biology has "arrived." Not so. By analogy to computer science, "biology is in the vacuum-tube stage," says Stephen Quake, associate professor of applied physics and physics. "An automatic genome sequencer or drug-discovery system fills a room, and requires a bunch of technicians to monitor it. It's roboticized large-volume fluid-handling, roughly equivalent to a vacuum-tube computer." So Quake and Axel Scherer, the Neches Professor of Electrical Engineering, Applied Physics, and Physics, are creating biology's equivalent of integrated circuits—the silicon brains in your PC, albeit not quite that sophisticated yet. Computers can process reams of data in parallel, to look for comparable gene sequences in different species, for example, but there's no way to do the lab work on even a remotely similar scale. It's all in the plumbing—dispense and mix, dispense and mix, over and over and over and over again—and, without the fluid equivalent of a number cruncher, "most biology students spend their career pipetting all day long," says Quake. "We're trying to free them for higher-level tasks." (On the consumer side, a "lab on a chip" the size of a flip phone could analyze the proteins in a saliva sample and tell you whether you have the flu or just a bad cold.)

The integrated circuit shrank a gymnasium-filling computer to fit on a fingernail. For the last decade or so, people have been trying to create integrated microfluidics, using the same technology to carve teeny-tiny pipes and build itty-bitty valves. But water (and its cargo of cells, proteins, or DNA) has proven much harder to push around than electrons. The problem is the valves—it's not called solid-state electronics for nothing. Everything is carved out of a single chunk of silicon and generally needs to remain attached to it. Imagine trying to insert a tiny gate valve into a tiny pivot hole under an electron microscope; now imagine doing it ten thousand times on a single chip without running screaming from the factory. So instead of hinged valves, people tried cantilevers—think of a pool cover that's mounted like a diving board. Explains Scherer, "Silicon is rather stiff, so to move it, as in a valve, you need to push on a rather large surface area. Otherwise, you're going to have enormous problems trying to apply enough pressure to deflect it." And the valve is going to leak if it doesn't close against a compressible gasket to form a tight seal.

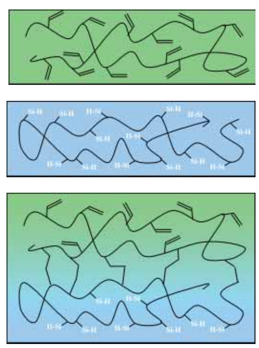
"We *tried* to make them out of silicon dioxide," recalls Scherer. "Then we tried to make them out of photoresist. Then we tried to make them out of polyimide, and then in the end we realized that the way of the future was bathroom caulk." "Rubber," Quake chimes in. Actually, it's PDMS, short for poly(dimethylsiloxane), a watertight sealant used on electronic components. Liquid PDMS has the consistency of maple syrup, so you basically make a mold with the fluid channels sticking up in relief from the bottom, pour the goop in, and bake it till it sets. Then you carefully peel the rubber off and reuse the mold. This method, called "soft lithography," was developed at MIT by George Whitesides (PhD '64).

But it took three innovations to make a functioning valve. Todd Thorsen (PhD '03), now at MIT himself, began working on a basic valve structure. The sample flows through a channel in the surface of the rubber, which is sealed, channel side down, onto a microscope slide. A control channel runs perpendicular to the one containing the fluid and very slightly above it, so that the thinnest of membranes separates them where they cross. "The



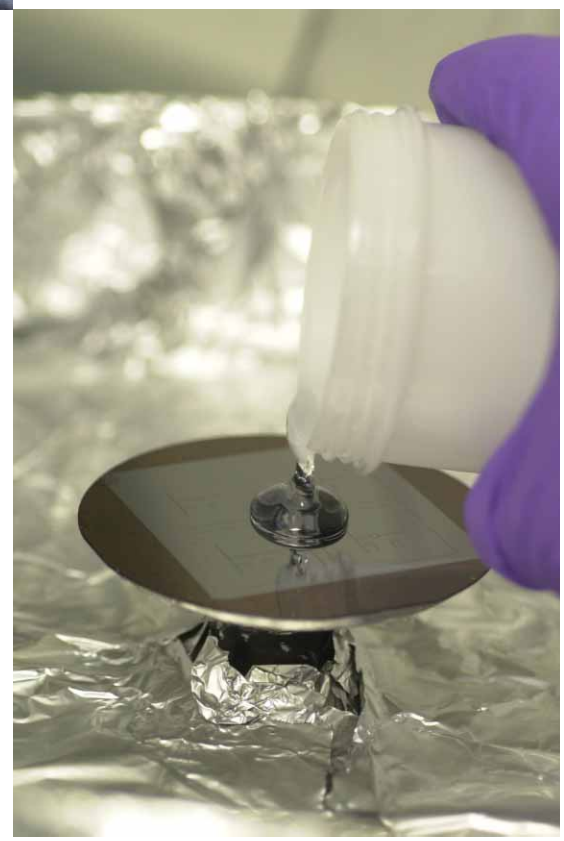


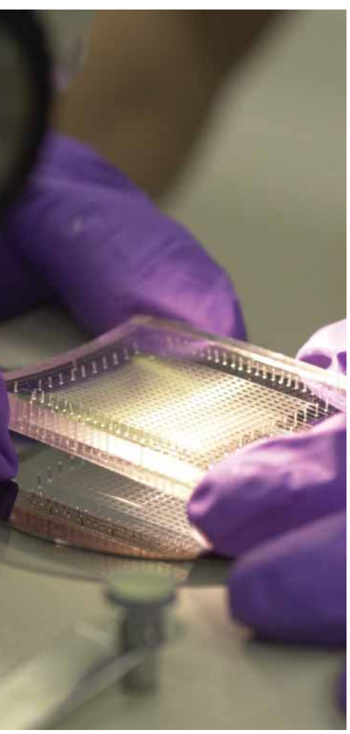
notion was that we could deflect the membrane and seal the bottom channel by applying pressure in the top channel. It's like stepping on a garden hose," says Quake. Making the control channel proved baffling, however, until Marc Unger (PhD '99) realized that each channel could be made in its own layer. PDMS comes as two components that have to be mixed, so Unger cast one layer with an excess of Component A and the other with too much Component B, cured them individually, and then sandwiched them together. A second heating then fused the two layers as the leftovers reacted.



"Then," says Quake, "we couldn't get the valves to close all the way. And Hou-Pu Chou [MS '96, PhD '00] had a key insight, which was to fabricate rounded channels instead of square ones." Step on a big tin can with the top and bottom removed and it squashes flat; step on a one-gallon plastic milk jug and the corners tend to keep sticking up.

The molds are created with standard chipmaking techniques. You start with a blank silicon wafer, to which is applied 10 microns of a resin called photoresist, which will form the channels. (A micron is a millionth of a meter, about the thickness of the aluminized skin of a birthday balloon.) To ensure a nice, even layer you spin-cast the resin, pouring it onto the rotating wafer's center and letting centrifugal force do the rest. The faster the spinner, the thinner the layer—to as thin as one micron, with very precise control. (Ironically, this enabler of advanced technology is a dead ringer for a portable phonograph from about 1967. Remember 45s, man? Groovy.) A mask printed by a laser printer supplies the channel

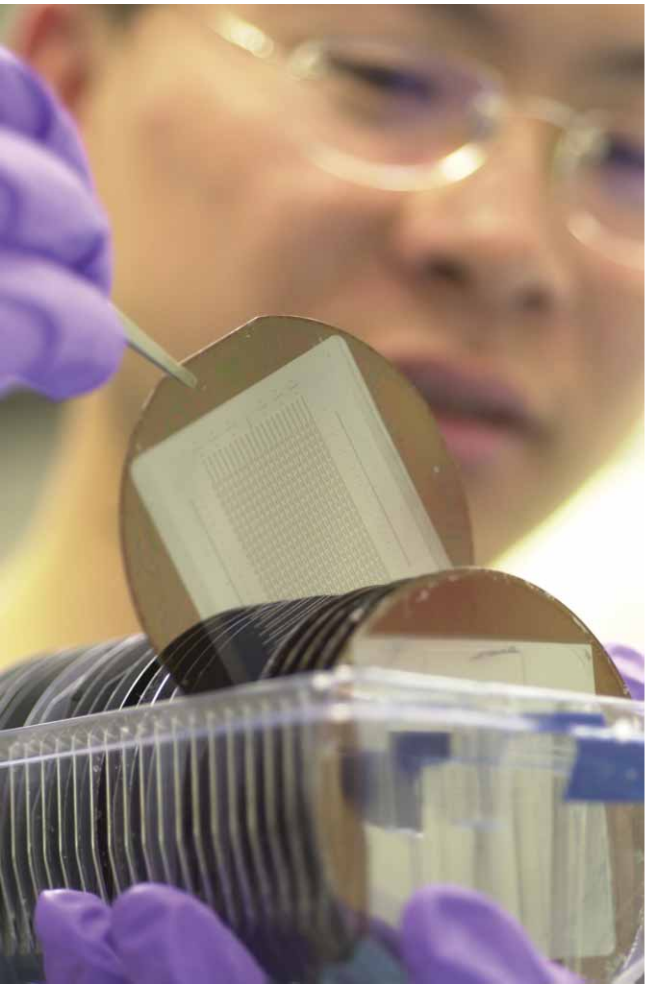




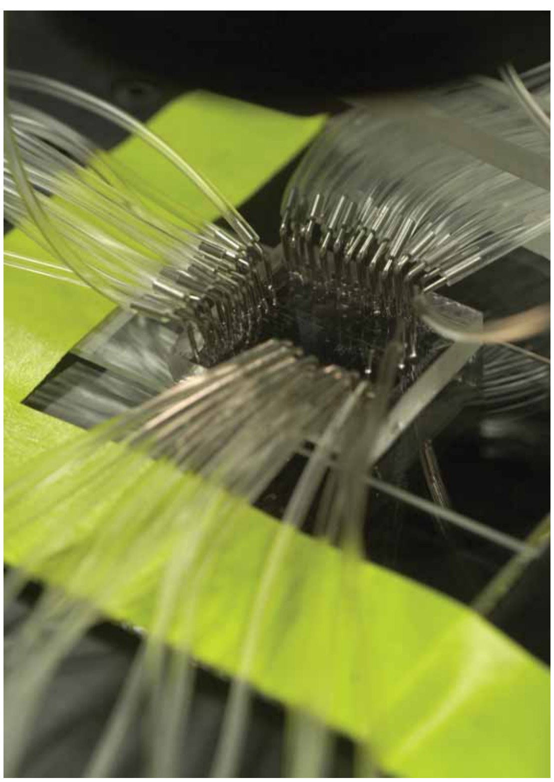
Top left: The microfluidics portion of Quake's research group. From left: grad students Michael van Dam, Jian Liu, Emil Kartalov (BS '98, with wafer), and Sebastian Maerkl; postdoc Jong Wook Hong; Quake (foreground); grad students Carl Hansen (background) and Joshua Marcus.

Above: Pouring the goop on a mold before revving it up. Aluminum foil lines the spin-caster's turntable well, for obvious reasons.

Left: The rubber layers really do flex!



Ironically, this enabler of advanced technology is a dead ringer for a portable phonograph from about 1967. Remember 45s, man? Groovy.

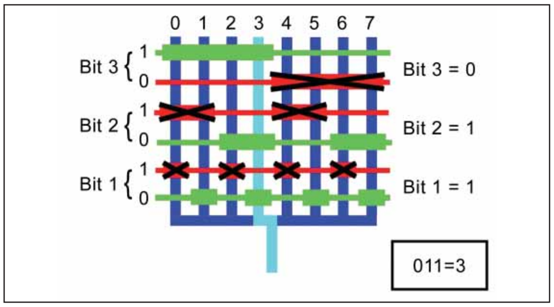


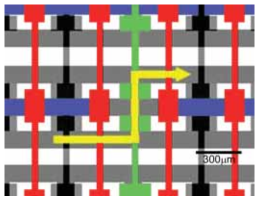
Above: Liu plays disk jockey, selecting a mold from the collection. The lab has enough of them to stock several jukeboxes. Right: A working chip, with all its fluid and control lines plugged in.

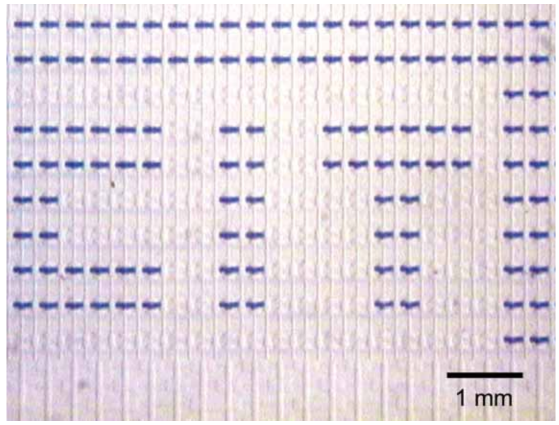
pattern in a process called photolithography; the resin is exposed to ultraviolet light through the mask, "developed," and rinsed to leave only the raised, square-sided lines of hardened photoresist. Then a quick heat treatment softens the photoresist just a tad, rounding the lines' corners. The fluid-layer rubber, which is perhaps 20 microns thick, is also spin-cast, but the control layer, which can be half a centimeter thick, is just poured by eye.

After curing, the two layers are aligned under a microscope before their second baking seals them to each other and to the slide below. Hollow steel pins—the same stock used for syringe needles—form the completed chip's connections to the outside world. You prepunch the pinholes in the control layer before making the sandwich; holes going into the fluid layer are punched through the assembled stack. Then you stick the pins in, and—thhhp!—the rubber just seals itself to them. This is a huge advantage, says Unger. "Imagine trying to epoxy a glass capillary the size of a grasshopper's shin onto a hole the same size—that's what people used to have to do." And aside from the mold making, which is best done in a clean room, "it's technology you could do in your garage," says Scherer. Assuming, of course, that there's room among the half-finished projects on your workbench for a record player, a microscope, and a small oven.

Besides not needing a high-tech vacuum chamber and a good eye with the epoxy, rubber chips have several critical advantages over silicon. You can do the whole process in a day, from designing the masks to testing the product, so it's easy to evolve designs. Or, you can reuse the same mold indefinitely, says Quake, "until you drop it and crack it." But most important, PDMS is gas-permeable—as the channels fill, the trapped air just seeps away. On a silicon chip, every dead end needs a vent line, and you can *still* wind up with channel-clogging bubbles. And caulk is cheap—







Clockwise, from the top: A. How a multiplexor works. The red and green lines are the control lines, with the red lines under pressure and the Xs marking the closed valves. The blue lines are the fluid lines, with the light blue one (number three, binary 011) being the only one open. In general, *n* fluid lines can be worked by $2\log_2 n$ control lines. B. To demonstrate selective addressing, blue dye was loaded into the memory chip and then individual chambers were purged with clear water to spell out CIT. Each chamber holds about 250 picoliters. C. The entire memory chip can be loaded (blue) in one shot by opening the red valves. To retrieve a sample, the row multiplexor sends pressurized water (yellow arrow) into the fluid line (gray) below the desired sample row, and the column multiplexor opens the green valves above and below the proper chamber.

about 50 times less expensive than silicon. So you could crank popular chips out by the truckload, but making custom ones isn't prohibitively expensive either.

Recalls Scherer, "Once we developed a valve and a pump, Steve ran with it." (A pump is just three sequential valves, opened and closed in the proper order.) "You can do a *lot* with two layers," says Quake. "However, we've shown that we can do up to eight, just by alternating A and B. I don't think there's really much of a limit." Adds Scherer, "It's just a matter of aligning them on top of one another." Two layers are enough to make chips that can store or process many subnanoliter samples at once, in layouts that rather resemble their silicon counterparts. (A nanoliter is one billionth of a liter—about one-thousandth the size of a sneezed aerosol droplet.)

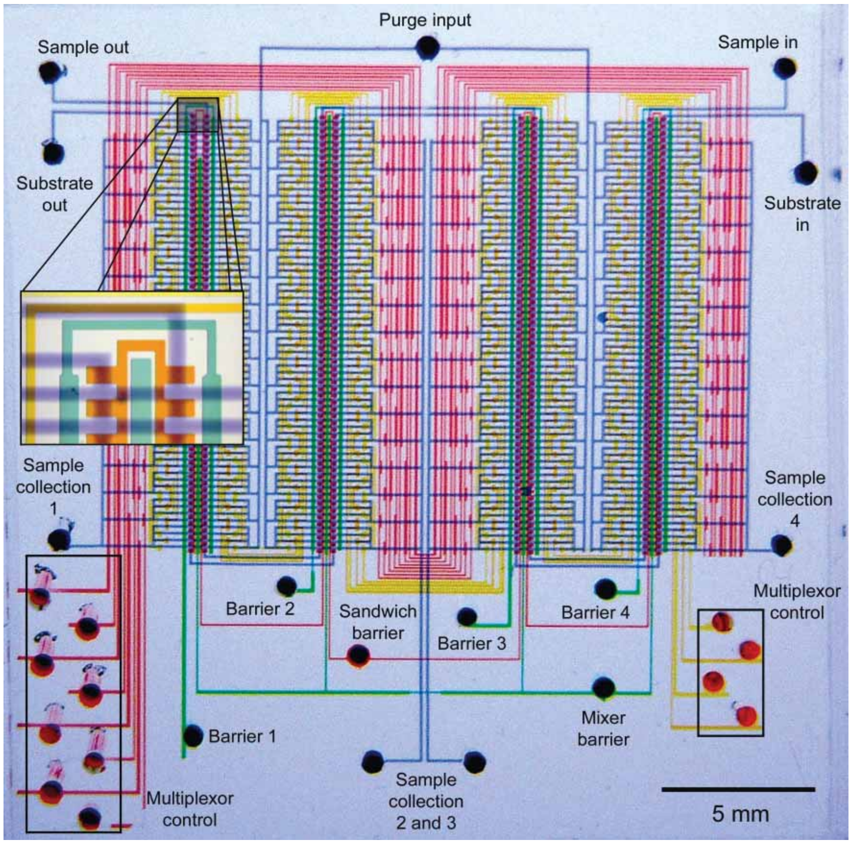
A single chamber can have several valves, so if each valve needed its own control line, the plumbing nightmare would seriously limit the number of chambers that could be put on a chip. One control line can shut many valves at once, which simplifies things. But if you want to shut a specific valve in the grid's interior, the control line may have to cross many fluid lines you don't want to affect. Fortunately, it's easier to make a wide channel bulge than a narrow one, so the control lines look like piano keys laid end to end, with the wide parts being the valves and the narrow parts merely crossovers. This ability to step on some hoses while striding over others is the key to managing complexity.

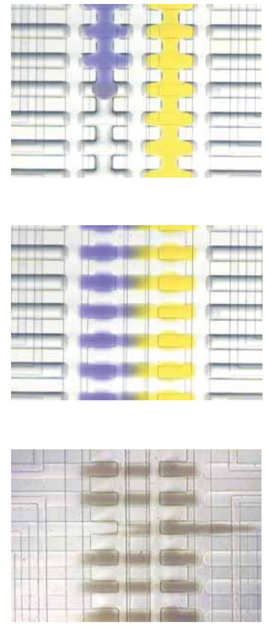
Even so, as you scale up the grid, the number of valves quickly gets out of hand. Quake and his cohort designed a multiplexor that allows all the valves in the grid to be controlled by a handful of valves on the periphery. A computer uses binary numbers—strings of ones and zeros—to "address" specific locations. The multiplexor does the same, except that it needs two control lines per digit. The first line represents the "one" state, in which, for example, all the even-numbered valves are closed. The other line represents the "zero" state, in which the even valves are open and the *odd*-numbered valves are closed. As a demonstration, Thorsen, grad student Sebastian Maerkl, and Quake cast a 1,000-chamber memory chip—a 25 × 40 grid—addressed by a mere 20 lines. By sending the appropriate pair of binary numbers to its row and column multiplexors, you can fill or flush any desired chamber without disturbing the others.

The trio also built a prototype 256-unit processor consisting of four pairs of columns of 64 chambers each. The contents of the chambers in adjoining columns get mixed pairwise, and the result from any one pair can be pumped out. As a test, one column was loaded with *E. coli* bacteria containing a mutant enzyme, at a bacterial density such that there was, on average, one bacterium every five chambers. The other column was loaded with a dye that, when oxidized by the enzyme, fluoresced bright green. By draining only the chambers that lit up, the mutant cells were collected in a highly concentrated solution. (An earlier cell sorter built by Anne Yen-Chen Fu, PhD '02; Charles Spence, PhD '02; Frances Arnold, the Dickinson Professor of Chemical Engineering and Biochemistry; and Quake used a T-shaped channel with a valve on each arm of the crossbar. Fluid was pumped up the T's leg, and the fluorescing cells were diverted one by one into the proper arm by opening and closing the valves.)

Besides checking for biological activity or concentrating samples, the processor can also split them up—perhaps dividing a diverse cellular stew into tiny subsamples that can be analyzed independently. ("Simplification by partitioning," Quake calls it.) It can also do chemical reactions in parallel, including "combinatorial synthesis," in which you mix and match, say, amino acids to make all possible protein sequences of a given length at once. In fact, grad student Michael van

These four illustrations reprinted with permission from Thorsen et al. *Science*, 298, p. 582. © 2002, American Association for the Advancement of Science.





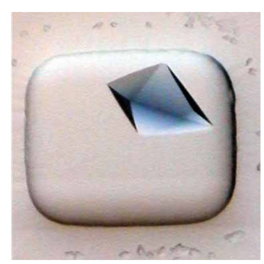
Right: The plumbing diagram for the processing chip, photographed by injecting food coloring into the various lines. ("Substrate" refers to the material the samples are going to react with, and the numbers identify the column pairs.)

Far right: With all the vertical valves closed, a sample column is loaded with blue dye and the adjoining substrate column with yellow (top). The barrier valves separating the two columns are opened, and the dyes mix (middle). The product from any given reaction pair can be purged to the sample collector (bottom).

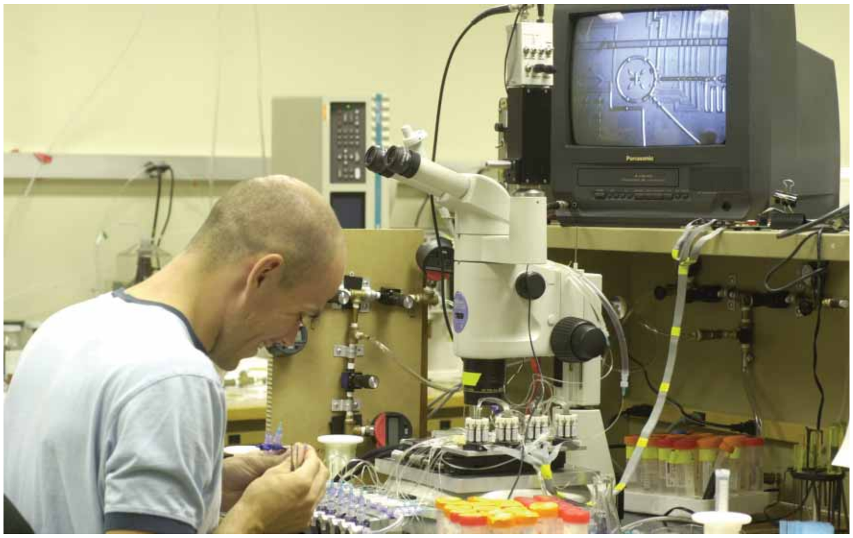
Dam wants to make a universal gene-detection chip that would contain samples of all possible single-stranded DNA sequences. When the gene you're looking for gets turned on, it would start cranking out RNA copies that would bind to the complementary DNA somewhere on that chip. But to conclusively isolate a gene, the DNA would have to contain enough letters so that the RNA only binds to one sequence. Depending on the complexity of your organism, this number ranges from 10 to 16 letters, or 1 million to 64 million sequences—rather more chambers than can be put on a chip at the moment, but perhaps attainable within the lifetime of a grad student.

It may come as no surprise that a start-up company has been formed; Fluidigm's first product, a protein crystallizer, hit the market in March. Proteins are a cell's molecular machines, but what a protein does—or fails to do—depends on the structure's excruciating details: one hydrogen atom out of place can kill it. And the best way to determine a protein's precise 3-D structure is by X-ray diffraction, which requires a high-quality crystal about 100 microns on a side. But there's no way to predict the conditions under which a protein will crystallize, so trial and error is the order of the day. Finicky is the word—crystallization frustration is the leading cause of hair loss among structural biologists, not to mention carpal tunnel syndrome from all the pipetting.

Fluidigm's design, based on one by grad student Carl Hansen; postdoc Emmanuel Skordalakes and professor James Berger, at Berkeley; and Quake, has 48 units, each of which can be loaded with a different set of crystallizing reagents. Further, each unit contains three pairs of mixing chambers of assorted sizes to give a range of mixing ratios. When you open the valves separating each chamber pair, the contents mix by diffusion. This is how crystals grow on the space shuttle, but it's well-nigh impossible to do on Earth because any sample much larger than these falls prey to convection, whose turbulent motion can jar the protein molecules out of solution into a noncrystalline glop. The slower the growth, the better the crystal, and gentle diffusion lulls the protein into remaining in solution long after it should have fallen out. It's like Wile E. Coyote running off a cliff—as long as he doesn't look down, he can keep going. Sometimes the chips even grow beautiful, diffraction-ready crystals under conditions that give glop in conventional experiments. And they do this with minuscule amounts



A protein crystal. If you see one you like, just slice open its chamber, suck it out with a micropipette, and pop it in the X-ray diffractometer.

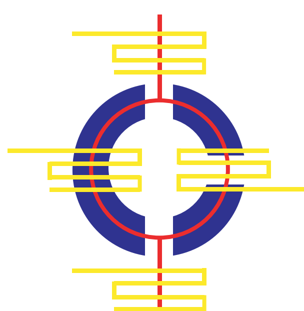


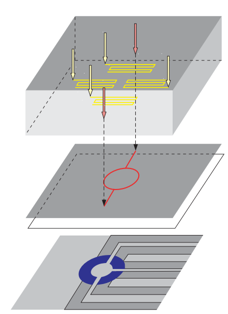
Right: Hansen at a microfluidics lab station. The chip is under the microscope, whose view is displayed on the monitor. Far right: The clustered cylinders that look like firecrackers are computer-driven controllers, developed by Fluidigm, that provide compressed air to pressurize the water in the chip's control lines. The array of white-handled valves in the foreground supply the fluids the chip is processing.

of protein—three microliters will supply all 144 experiments on the chip.

So—does anyone outside the world of biotech care? Well, the cops might. Grad student Jian Liu, then-postdoc Markus Enzelberger, and Quake have developed a potentially handheld PCR reactor. PCR stands for polymerase chain reaction, which allows you to make millions of copies of a single piece of DNA quickly and easily and which won Kary Mullis the 1993 Nobel Prize in chemistry. Conventional PCR machines are as big as toaster ovens and use microliters (millionths of a liter) of fluid; depending on the procedure used, one complete cycle can take from a few minutes to a couple of hours. (The first cycle yields one DNA copy; the second, four; then eight, sixteen, and so on.) It takes 30 cycles or more to get a usable amount of DNA from a single drop of blood, and Caltech's chip, which used a record-setting 12 nanoliters of sample, can run at about 30 seconds per cycle. Thus a readout could be ready in 30 minutes or so, far less time than *CSI*'s Catherine Willows spends at the average homicide. And PCR is morbidly sensitive to cross-contamination, so a sealed "lab on a chip" you could take to the crime scene, use once, and discard would make positive matches much more positive. The coroner's office could save some big bucks into the bargain—PCR reagents are very pricey, so consuming them by the bottle cap instead of the bottle would make the budget go a lot farther.

The design is based on a ring-shaped mixer developed by Chou, Unger, and Quake back in the early days. As the liquid courses around the circle, it passes over tungsten heating elements set to the proper temperatures. (PCR methods vary, but there are two or three steps that run at different temperatures, including one near boiling.) In the current design, the reagents swirl with the sample. But if the DNA polymerase—a heat-sensitive enzyme—could be confined to the chip's middle-temperature region, the reaction could use faster polymerase strains that are even less stable when heated. In fact, pretty much any medical and most biotech applications you can imagine, like van Dam's gene detector, would benefit from being able to attach proteins, DNA, or what-have-you to the chip. This can be done with avidin, a protein found in egg whites, and biotin, a growth factor—also known as vitamin B_7—that comes from the yolk. Avidin and biotin bind strongly and exclusively to each other and, says Quake, "there are tons of enzymes and other proteins that have been 'biotinylated,' and you can biotinylate DNA molecules. So if you have a way to attach avidin to a surface, you can catch all these things. It's like the Krazy Glue of biology." It works the other way, too—you can put biotin on the glass





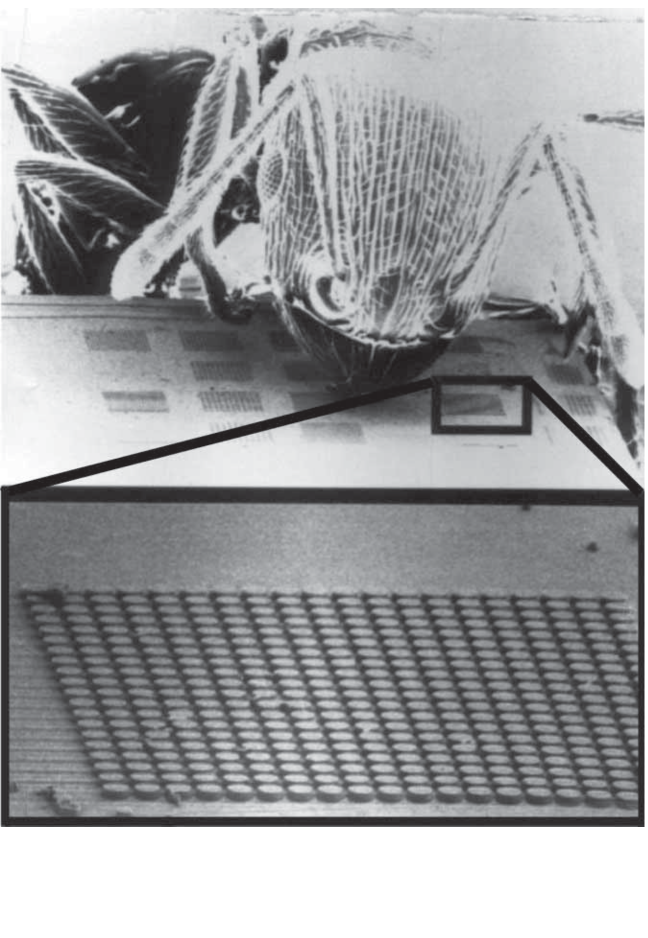
The layout plan (right) and assembly diagram (far right) for the PCR chip. The red line is the fluid channel, which can be made in varying widths so that the sample lingers for the correct time over each heater (blue). Liu designed the S-shaped pumps (yellow) after noticing that a control line inflates from one end to the other, like those long, thin balloons used to make balloon animals. One S thus does the work of three parallel lines pressurized in sequence, helping reduce the plumbing's complexity.

The goal is to take a solid-state laser and a digital camera and make a silicon sandwich, with the plumbing being the peanut butter.

(or silicon) to affix avidin-anchored antibodies. Either way, you just make a rubber layer whose channels take the avidin or biotin to where you want to attach it. Once it's bonded, you peel the rubber off and put the real chip together.

Quake, whose background is in biophysics, came to Caltech to work on ways to manipulate individual biomolecules, such as DNA strands; meeting Scherer crystallized his interest in using microfluidic chips for the job. Scherer, a solid-state physicist, came to Caltech in 1993 after eight years at Bellcore, where he coinvented a surface-emitting microlaser—essentially a five-micron-tall, one-micron-diameter tower of hundreds of semiconductor layers stacked like poker chips. When a current passes through the stack, a laser beam shoots out the top. Until Quake's arrival in 1996, Scherer was developing microlaser arrays for communications networks and, perhaps, optical computers. "Axel helped mentor me when I got here," Quake recalls. Says Scherer, "Initially, a lot of the photolithography was done in my lab." Laughs Quake, "We wore out our welcome." "They were monopolizing our optical mask aligner," Scherer shoots back. "He was overrun with grad students," Quake agrees. "So it was better to make a parallel effort," Scherer concludes, "and it's worked very well."

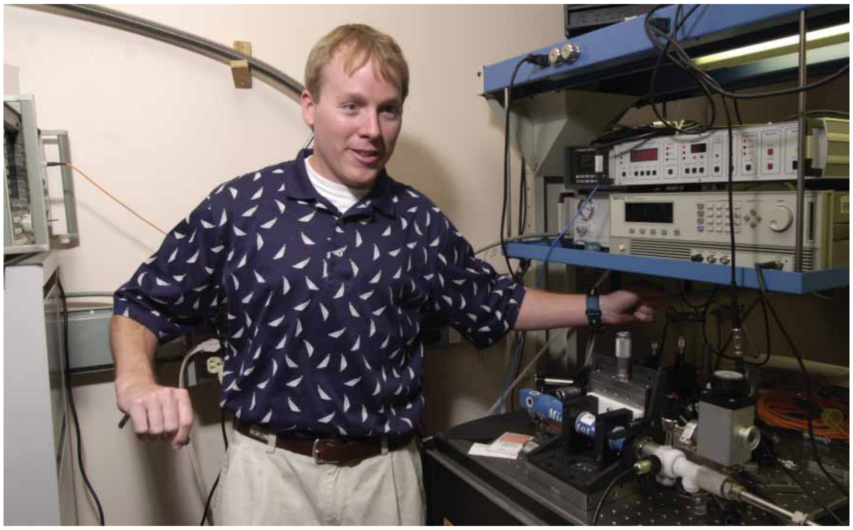
"The original idea was to make ultrasensitive analytical tools using single-molecule spectroscopy," says Quake. "As we started moving farther up the food chain, we split efforts—I tried to optimize the plumbing part, and Axel's been trying to optimize the sensor part, and now we're in the process of knitting them back together."



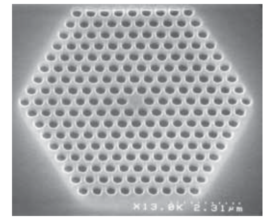
Left: An Argentine ant—those little guys about three millimeters long found in every back yard in L.A.—inspects a chip containing several arrays of Scherer's surface-emitting microlasers.

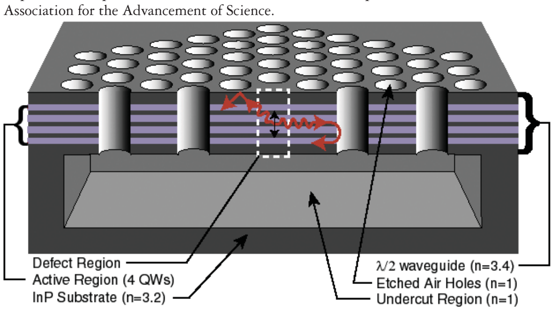
A typical sensor includes a light source and a detector—you shoot light through the sample, which either absorbs some or fluoresces. Either way, the particular wavelengths involved fingerprint the sample, and the signal strength tells you how much of it you've got. So the goal is to take a solid-state laser and a digital camera and make a silicon sandwich, with the plumbing being the peanut butter.

The laser technology revolves around "photonic crystals." At the turn of the 20th century, the father-and-son team of Sir William and Sir Lawrence Bragg invented X-ray diffraction crystallography, for which they shared the Nobel in 1915. As mentioned earlier, this is the method of choice for determining protein structures, and it works because an X ray having a wavelength roughly the same as the spacing between the atoms in a crystal will be diffracted by them into patterns that reveal their arrangement. More generally, electromagnetic radiation of any wavelength can be reflected, diffracted, or focused by a lattice of "atoms" of the proper size and spacing—a photonic crystal. So a properly constructed silicon wafer with islands of some other material embedded in it can trap and concentrate light into a volume 100 times smaller than a cubic



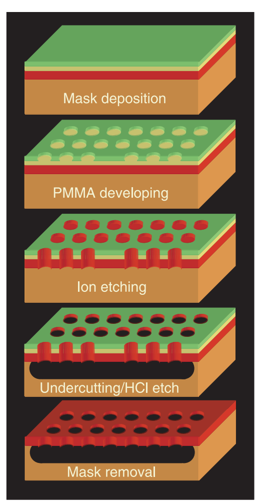
Adams with the apparatus (left) used to test the defect-cavity lasers (below).





Left: A cross section through a defect-cavity laser. Light gets trapped in the waveguide's central region, because it's reflected wherever it meets a sharp change in the refractive index (n). (QW stands for quantum well, of which there is one in every red band in the active region, and λ/2 means one-half a wavelength.)

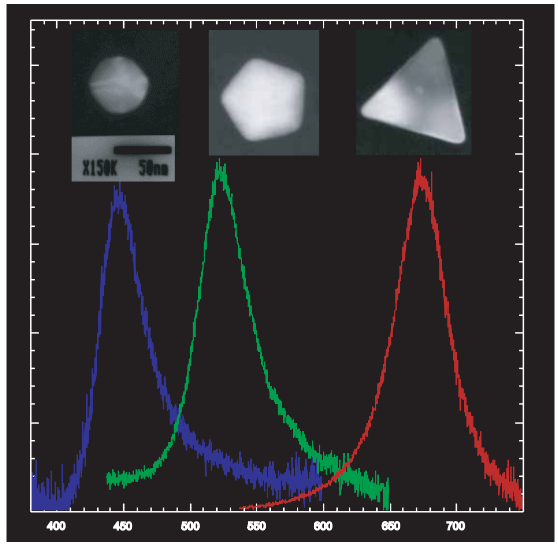
Right: Making a microlaser chip is a bit more complicated than making a microfluidic chip, but it's still all standard technology. The green layer is polymethyl methacrylate (PMMA), a photoresist that is patterned by a scanning electron microscope's electron beam. Then a highly reactive beam of fluorine or chlorine ions drills through what will be the photonic crystal (red) to the silicon base (brown). A nice acid soak then opens up the air space underneath. (The yellow layer is a second kind of mask.)



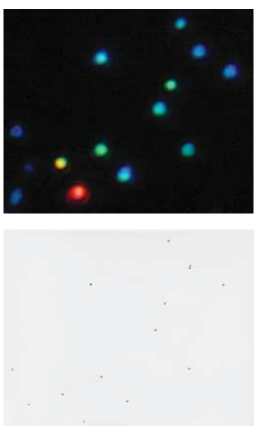
wavelength. You just make the wafer half a wavelength thick, with air above and below it. The silicon-air interface acts like a mirror, confining the light within the crystal, where Bragg reflection does the rest. (Of course, the trapping material has to be transparent, so for silicon this only works in the infrared, which is to silicon as visible light is to glass.)

Oskar Painter (MS '95, PhD '01), now an assistant professor of applied physics; Reginald Lee (MS '96); Scherer; and Amnon Yariv, the Summerfield Professor of Applied Physics, realized that it would be a lot easier to make the entire crystal out of silicon-air interfaces—all you needed to do was drill a bunch of holes in it. The resulting "defect cavity" is a hexagonal array of holes, not unlike a honeycomb, surrounding an un-drilled-out space in the center. That missing hole is the "defect," and it traps light. It's a "cavity" only in the optical sense, because the light within it behaves as if between a set of mirrors. The light resonates, amplifies, and, as with the microlasing pillars, eventually shoots out the surface. Voilà—a nice, flat laser that could be sealed to a rubber layer.

Meanwhile, postdoc Enzelberger and Scherer's grad student Mark Adams (MS '00) were laying rubber on the latest spaceflight-quality camera chips provided by Robert Stirbl at JPL's Microdevices Lab. But the narrower the channel, the shorter the path light takes through the sample and the less sensitive the sensor becomes. The simplest way to keep the sample in the beam longer is to make a hole in the cavity, redundant as it sounds, in order to collect the fluid. But would a defective defect still act as a laser? Nobody knew, and the odds didn't look good, but Marko Loncar (MS '98, PhD '03) took on the challenge. Says Scherer, "that was a two-year design process all in itself, trying to make a high-resonance cavity with a hole in it." Amazingly, it worked, and it created a third way of analyzing the sample beyond fluorescence and absorption. The fluid



Right: Zooming in with high-magnification TEM reveals the shapes of individual particles. (The scale bar is 50 nanometers.) Each particle's visible-light spectrum is shown below it. Wavelengths are in nanometers.



Below: The plasmon particles are awfully pretty when seen by a dark-field microscope (top), but are barely visible under a transmission electron microscope (TEM) at the same magnification (bottom).

alters the laser's wavelength in very specific ways—alcohols are different from water, and proteins are different from one another. "You couldn't do this by drilling a hole in a relatively big laser, like the one in a laser pointer," says Scherer, "because there are just too many states available to the system. But here there are only a few available states, so you can deconvolute it."

Another method may work with visible light. Postdoc Mladen Barbic is experimenting with flecks of silver some 50 nanometers (about one-tenth the wavelength of green light) in diameter. Through a phenomenon called "plasmon resonance," their shapes govern the colors of light they absorb and reemit—circles turn blue, pentagons green, and equilateral triangles red. When a molecule from the sample attaches itself to one of the metal particles, it alters how the light behaves by a process called surface-enhanced resonant Raman scattering (don't ask). When you hit the metal-molecule combo with a laser, you get a spectrum containing many sharp peaks that identify the molecule, and the particle amplifies the spectrum so that even single molecules can be seen. Barbic currently makes what is essentially very small pocket change by chemical means, but the particles come out in assorted shapes and, when seen on a darkened microscope stage, look like the world's tiniest Christmas lights. He'll shortly carve them to order out of a silver layer deposited on a silicon wafer, using the brand-new, state-of-the-art clean room that Scherer and Professor of Physics Michael Roukes have just gotten built.

Quake and Scherer are close to putting the optics, fluidics, and electronics all on one chip. One needs to be clever planning the plumbing, of course, so that the only hole the fluid channel passes over is the one in the defect, but this is a minor detail. In a year or so, a rubber multiplexor could be sandwiched between a camera array and a laser array, with each laser drilled to a different wavelength. The multiplexor would shunt the sample to the appropriate lasers, and you'd have a microanalyzer. Another year to build in a processor as well, and a true general-purpose lab on a chip is born.

Meanwhile, word is getting out. Says Scherer, "Our biggest problem right now is that we've become *too* successful. We're making structures that are in high demand." "People are banging on our doors," Quake agrees. "And not just from on campus, but actually from around the world." So rather than open up a sweatshop filled with grad students, the soft-lithography fab lab is available to anyone on campus. And part of the recent Moore gift has been earmarked for a "foundry," where a full-time technician will mass-produce chips, or make them to order based on Ath-napkin doodles. Says Scherer, "We're very excited about having this technology transferred to the biologists on campus."

The current designs have fluid channels 100 microns wide and handle samples of a couple dozen nanoliters. Scherer and Quake are aiming for one-micron channels, about the size of an *E. coli* bacterium, which translates into femtoliter (trillionths of a liter) volumes. Such fine masks can be made with off-the-shelf equipment—one micron is as wide as a highway, by silicon standards. So there's plenty of room at the bottom, as Richard Feynman famously remarked in these very pages. Says Quake, "These devices obey a Moore's-law-type scaling—in fact, they beat the conventional semiconductor Moore's law by quite a bit." (Moore's law says that advances in technology allow the number of transistors, or in this case valves, on a chip to double every 18 months.) "So we can now start to count on this happening, and we should start planning what kind of devices we can make with that. On the other hand, it's worth spending the effort in technology development to make sure we stay on track." Adds Scherer, "The exciting part is that so little has been done that

Right: Scherer's and Roukes's new clean room is rated Class 100, meaning it has less than 100 dust particles per cubic foot of air. (Typical Pasadena air might contain a million particles per cubic foot; if you have an indoor air filter, you might be breathing Class 50,000 air.) The equipment is still being broken in, but the air samples are already in the Class 10 range, and they hope to get to under four. Loncar grips the access door to the e-beam writer, which can aim a 13-nanometer-diameter electron beam to 0.6-nanometer accuracy anywhere on the surface of a standard six-inch wafer, allowing you to write several successive patterns in perfect register. The entire system is mounted on its own concrete foundation pier so that people's footfalls don't jar it.

Scherer the silicon chef.

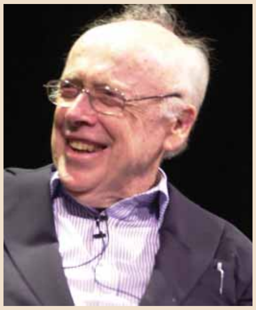
PICTURE CREDITS:
8 – Sebastian Maerkl; 9, 10 – Fluidigm; 10, 11, 14, 16, 18 – Bob Paz; 14 – Doug Cummings; 12 – Doug Smith; 13 – Carl Hansen; 15 – Axel Scherer

you can get a lot of mileage out of even small details."

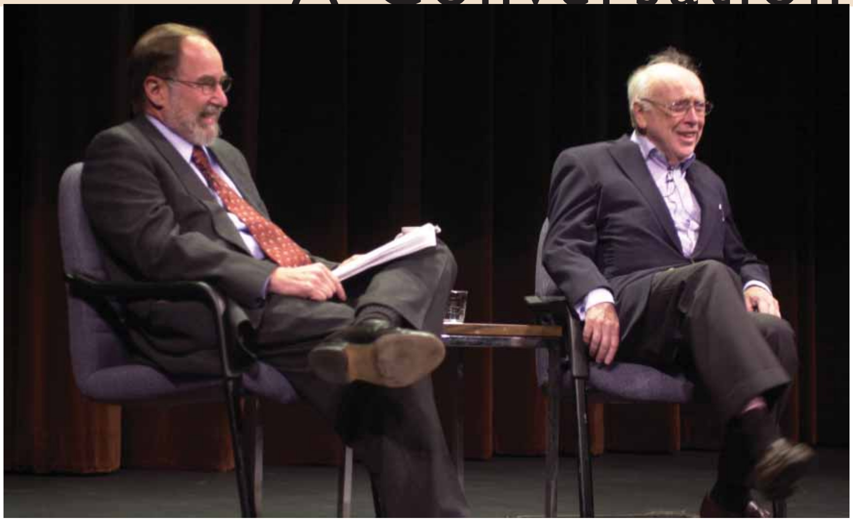
Eventually, of course, they'll hit the wall—literally. The layer of water molecules next to the channel wall tends to stick to it, so as the walls get closer and closer together, the free-flowing fluid region gets narrower and narrower, and at some point the pumps will no longer be able to force the passage. This doesn't occur in the one-micron channels that have been made as demos, so grad student David Barsic (MS '01) is trying to see just how narrow a channel can be. But Shapiro's law of cell sorting says that a 49-micron cell will plug a 50-micron channel, so for some uses there's no point in going smaller anyway.

"The tools are now here," says Scherer. "But the applications are in front of us. And that will drive the development of the next generation of tools. Caltech has a lead right now, but a lot of infrastructure has to be built, and we have to invest in order to take advantage of this moment." Adds Quake, "We've taken a five-year detour in technology development, and now it's mature enough to do science. We have a *lot* of things planned. In the near term, my group plans to look at unculturable bacteria. Ninety-nine percent of what surrounds us can't be grown in the lab, and therefore is sort of invisible. It's the biological equivalent of cold, dark matter." Taking a tack analogous to the protein crystallizer, Quake will collaborate with Jared Leadbetter, assistant professor of environmental microbiology, and David Relman at Stanford to learn what living conditions these little bugs like, to try to find out what they can teach us about the spectrum of life. "And we want to look at the human body's rarest cells, stem cells and such. It's difficult to analyze them with conventional techniques, because they occur in such small numbers. But we should be able to get detailed molecular and genetic characterizations of them with integrated microfluidics." For this, he's collaborating with W. French Anderson, director of the Gene Therapy Laboratories at USC.

"Integrated circuits automated the process of computation," says Quake. "During World War II, people wanted to solve differential equations in order to compute missile trajectories. They did this with teams of people with adding machines." So ENIAC, the world's first electronic digital computer, was built at the University of Pennsylvania in 1946. Weighing over 30 tons, including its power supply and air-conditioning units, ENIAC contained 19,000 vacuum tubes and 1,500 relays, and drew about as much power as 200 households. With that, it could add, subtract, multiply, divide, and do square roots on twenty 10-digit (base-10) numbers simultaneously, and there was much rejoicing. Then the transistor came along, followed by the integrated circuit and eventually the PC revolution. "And all of a sudden people realized that automated computation was not just useful for solving math problems, but could be used for word processing, spreadsheets, e-mail, the World Wide Web, and Tomb Raider. Nobody anticipated that when they started this program of automating math. In comparison, our lab is now in the '70s. We have specific large-scale integrated circuits for certain tasks, but we don't yet have a general-purpose programmable microprocessor." But with Moore's law holding sway, the '90s aren't far off, and who knows what the fluidic equivalent of a Pentium will bring? □



A Conversation with Jim Watson



On May 5, James D. Watson stopped by Caltech for a "conversation" with President David Baltimore on the occasion of the 50th anniversary of Watson and Crick's discovery of the structure of DNA. Watson, who normally commands speaker fees up to $25,000, which he donates to the Cold Spring Harbor Laboratory, happened to be in Pasadena on a bookstore tour to sign his new book, *DNA: The Secret of Life* (which itself was conceived to mark the anniversary), and Baltimore invited him back to campus for a visit (Watson spent two years at Caltech just after his famous discovery). The spur-of-the-moment invitation packed Beckman Auditorium in the late afternoon with an audience eager to hear Baltimore and Watson discuss questions that would "range over history, concentrate a little on Caltech-related events, people, and of course on the discovery of the DNA structure."

Watson was interested in birds when he entered the University of Chicago in 1943, but, said Baltimore "he clearly must have understood that there was a revolution inherent in the concept of the gene." He asked Watson if any of his teachers had influenced him in thinking about the gene. No, replied Watson; the biggest influence was Erwin Schrödinger's book *What Is Life?*, which named genes as the key to understanding what life was. After reading it in 1946, he went on to graduate school at the University of Indiana ("Harvard accepted me with no money," and "Caltech saw that I had a C in calculus") and took Salvador Luria's course on bacteriophages, viruses that were thought to be naked genes.

"It's sort of interesting that your background and my background were so affected by Luria," said Baltimore. "An extraordinary man."

Watson noted that Luria was very warm and supportive to his students, "but he wasn't warm to Republicans. He wasn't one of these people who was just warm in general; he was not a saint. He didn't like chemists, also."

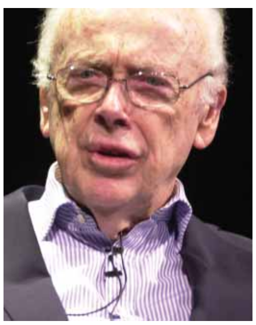
This brought Baltimore to his next question: "Your success was really a success of chemistry, and yet your background was that you got turned on by a physicist who studied biology. Where did you learn enough chemistry to figure out the structure of DNA?"

"Well, the structure is so simple, that's the only reason," replied Watson, to laughter from the audience. "You didn't have to be a good chemist to get the answer. I think if Francis [Crick] or I had known any chemistry, we would have proposed the double helix without the data [from Kings' College] because there was enough in the literature . . . you should have been led to the base pairs just from the data in the literature." But Jerry Donohue, a theoretical chemist who had come to Cambridge from Caltech, did steer them in the right direction by pointing out the correct structural form of the DNA bases, which allowed them to see the base pairing.

Baltimore remarked that the chemistry consult helped at the right moment. "Chemistry was essential," agreed Watson. "Cambridge was a great university, and if you were interested in X-ray work, it was *the* place to go. So that's why Jerry Donohue ended up there and why Francis and I ended up there."

PICTURE CREDITS:
19-20, 22-25 – Bob Paz;
21 – Caltech Archives

Before going on stage, Watson reminisces with Linda Pauling Kamb, described in *The Double Helix* as Peter Pauling's "beautiful blonde sister," who he thought would "undoubtedly liven up the Cambridge scene" in 1952, if she were to visit; and Seymour Benzer, the Boswell Professor of Neuroscience, Emeritus, whom Watson credits as one of the few who immediately sensed the importance of the double helix structure.



Baltimore mentioned the experiments by Oswald Avery: "One of the things I've always been curious about is why they didn't have the impact that they might have. The genetics community, particularly around Luria and [Max] Delbrück, never seemed to appreciate that Avery—this is now 1944—and his colleagues had published a paper that quite clearly showed that as chemically pure DNA as you could get would transfer genetic characteristics. And yet the idea that DNA was the carrier of genetic information really didn't take hold."

"I think it was just that everyone expected that proteins were going to be involved," said Watson. "And also the covalent backbone—how the nucleotides were linked together—wasn't established until '51. It was the Avery result that was the stimulus for [Erwin] Chargaff to measure the relative concentrations of DNA's four bases (adenine, guanine, thymine, and cytosine) and for Alex Todd to get his organic chemists to establish the covalent structure. But neither Luria nor Delbrück thought in terms of molecules.

"Luria thought chemists were just people who made money," Watson continued. "You know, the bright people were physicists and geneticists."

When the Hershey-Chase experiment in 1952 showed that DNA is the genetic material of phages and that proteins do not transmit genetic information, many scientists became convinced of the importance of DNA. But, said Watson, "it didn't convince Luria. It was very surprising that, when we found the base pairs and I wrote to both Luria and Delbrück, Delbrück was immensely excited. The moment he got the letter, he rushed to tell Linus [Pauling] what the answer was. But Salva was rather slow. He just didn't think in terms of chemistry. It was a foreign way of thinking."

Before the Hershey-Chase experiment, Watson had moved to Sir Lawrence Bragg's Cavendish Laboratory at Cambridge University (after a frustrating postdoc year to learn biochemistry under Herman Kalckar in Copenhagen), and had begun to tackle the structure of DNA. And he was encountering some interesting people around the continent. "I heard Maurice Wilkins in Naples in May 1951," Watson related. "As soon as that meeting was over, I went to Geneva, where I saw Jean Weigle, who had just come from Caltech to spend the summer there. And he told me of hearing Linus propose a clever structure for the polypeptide chain (the alpha helix). He said he didn't know whether Linus was right. So when I got back to Copenhagen, I went to the library and found the Pauling papers and read them. Soon afterwards Lawrence Bragg had been invited to give a lecture in Copenhagen, and he came and talked about Perutz's result with the message that Pauling was right. So by the time I got to Cambridge, I knew that Pauling had used model-building to get the alpha helix. So my first question to Francis was: could we use the model-building approach for DNA? And Francis said, why not? And then he wrote Maurice; would he come up? And so Maurice came up from London for a Sunday lunch and said he thought DNA was a helix and that it was multichained. And then he said that he was sort of being stopped from pursuing it because he and Rosalind Franklin didn't get on. He said Rosalind would be giving a talk, and I went and heard the talk. But, not knowing crystallography, I confused 'asymmetric unit' with 'unit cell,' and so had the water content wrong by 24. So we built a very dry model."

On April 25, 1953, Watson and Crick published their now-famous paper in *Nature* on the work that won them and Maurice Wilkins the Nobel Prize in 1962. In September 1953, Watson arrived at Caltech for a meeting that Pauling had organized on protein structure. He stayed on for two years, first on a postdoctoral fellowship with Delbrück; in the second year, George Beadle made him a senior research fellow in biology.

Baltimore noted that "the Meselson-Stahl experiment was, of course, done at Caltech in the late 1950s and is often considered to be the experiment that really proved that the DNA structure was correct."

Watson agreed. "I think it proved that its main implication was correct; that is, that the strands really come apart. And that was why everyone really got excited by the structure. It could have been pretty, but so what? But if the strands come apart, and you copy with A and T and G and C, then that was the important thing." Watson and Crick had suggested in their 1953 paper that the strands of the helix unzipped, providing a mechanism for copying genetic information, but the Meselson-Stahl experiment proved it. "It really didn't get the recognition it deserved," said Watson. "It should have gotten the Nobel Prize. It was an unbelievably important experiment. It really was the one that made most people want to study DNA. Until then people thought it was interesting, might be right, but almost no one changed what they were doing or started thinking in terms of the double helix. Seymour Benzer and Sydney Brenner—they were the people who really sensed the importance—and George Gamow. But in Cambridge—now it seems impossible to imagine—we had this structure, we sent the manuscript off in April, and no one asked us to give a seminar."

"But in Cambridge—now it seems impossible to imagine—we had this structure, we sent the manuscript off in April, and no one asked us to give a seminar."

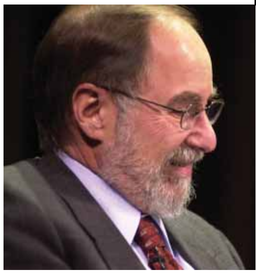
Baltimore asked Watson whether he gave a seminar at Caltech when he came here the following September. Yes, said Watson, about six weeks after arriving, and he had also given a talk at a Cold Spring Harbor symposium in June.

After his two years at Caltech, Watson left for Harvard, and in 1968 became director of the Cold Spring Harbor Laboratory, in New York. "You moved to Cold Spring Harbor," said Baltimore, "and I remember it was with a very clear idea of changing the direction of molecular biology toward mammalian biology and toward cancer. That was before recombinant DNA methods were available. It was before Howard Temin and I found reverse transcriptase. What did you think we were ready for at that time? Where did you see us going?"

Watson had been interested in SV40 polyoma virus, a small cancer-producing DNA virus, which appealed to him because it had a very small number of genes and he thought he might find mutants. But he conceded, in retrospect, that they would have gotten nowhere without recombinant DNA, the techniques for which weren't perfected until the early '70s.

"I remember your telling me about polyoma when I once drove you from Cold Spring Harbor into Manhattan," said Baltimore. "This was about

Linus Pauling's protein structure conference in September 1953 brought Jim Watson to Caltech, where he stayed for two years. Pauling stands third from left in the front row, with Watson directly behind him. Also in the photo are Maurice Wilkins (second row, far left) and Francis Crick (second row, fifth from left), who would share the Nobel with Watson in 1962; and John Kendrew (first row, far left) and Max Perutz (third row, second from left, next to Watson) who would share the Nobel Prize in chemistry, also in 1962. Sir Lawrence Bragg, director of the Cavendish, stands front row, center, in the white jacket.



“To put together a thousand [genes], you needed God, but with no God, you can say at some time it had to be simple.”

1959. And you thought that there might be one gene in there that caused cancer. Have you been surprised at how difficult it has been to find the genes that cause cancer?”

Watson replied, “Well, now we’ll find them all, but it’s a good rule that everything is five times harder than you think. When I spoke at the dedication of your new cancer center [at MIT], I said, ‘You know, you guys are doing a wonderful thing: you’re siting cancer research in a place where you’re doing real science and you’re not trying to cure people. And then my talk got in the papers as ‘War on Cancer Big Failure.’ But what I said was that MIT was the only pure scientific place that had established a cancer center. It was left to clinical places to do it, and the clinical places weren’t as good as MIT. It was a place where you brought real brains to bear on cancer. Caltech didn’t have the sense to do it.”

“No comment,” said Baltimore. “But there’s certainly truth in that. So, now cancer research has moved forward for 40 years since those days,” he continued. “Do you think that we now have enough basic science so that we can concentrate more on the applications of the science to the human problem of cancer?”

“You know,” replied Watson, “I may be a little nutty, but I actually believe that Judah Folkman’s ideas on antiangiogenesis [limiting the blood supply to tumors] will work. His antiangiogenic protein fragments, angiostatin and endostatin, certainly work in mice. So, if these proteins are normal regulators of cancer-cell growth, and if we went at it like the Manhattan Project, we could stop cancer in 10 years. But Judah, unfairly, is just thought of as a surgeon; he’s not a molecular biologist, so he’s pretty much ignored.” Watson offered to bet Baltimore (“as much money as you’ll bet against me—even odds”) that Folkman would turn out to be right.

“So in a sense, you’re saying you think we do have enough basic information,” said Baltimore.

Watson’s indirect answer to that was: “If I were a young person, I wouldn’t do cancer research.”

“What would you do?” asked Baltimore.

“Well, the brain. It’s obvious. That’s a no-brainer.”

“How about computational biology and all of the multiple integration methods?”

“Well, you know,” replied Watson, “you can do systems biology and prove that a cell works.”

“But you’re comfortable knowing it works already,” Baltimore assumed.

“Yeah,” said Watson. “We already know how it works. So all the sort of equations proving that it works just monumentally bore me.”

Watson went on to describe research that had determined that the bacterium *B. subtilis* has only about 250 genes essential to life. He said that in 1965 he had thought of a bacterial cell as a little machine and tried to figure out how many essential parts there were. He had guessed there would be about a thousand parts, or genes. The astounding fact that a bacterium can have as few as 250 necessary genes made sense, he thought, because “life had to get started. To put together a thousand, you needed God, but with no God, you can say at some time it had to be simple.”

The tiny bacterial genome led Baltimore to his next question: What did Watson think was the most important result to come from the Human Genome Project? [From 1989 to 1992, Watson was the first director of the National Center for Human Genome Research.]

Watson answered, “The linking of genes and behavior,” pointing in particular to studies on a potential gene for violence. In a study in the Netherlands, it was found that a gene for the enzyme monoamine oxidase, which destroys neurotransmitters, was inactive in violent males in one family. Subsequent research discovered a weak promoter and a strong promoter for the gene, he explained. A study of youths in New Zealand with a history of violence found that they

"There is a conflict between truth by revelation and truth by observation and experiment."

largely carried the weak promoter. Young people with the strong promoter, however, even those from violent, abusive homes, were unlikely to be aggressive.

Baltimore then asked: "What is the biggest ethical challenge that comes out of the kind of knowledge we're developing today?"

"I think it's that we're not using this knowledge," said Watson. He pointed out that the gene for fragile X, which causes the most common form of inherited mental retardation (one in 265 women carries the gene), is known, but no one is being screened for it. "To me, the ethical thing is we're being held back."

Baltimore: "Who's holding that back? Why is it being held back? Is it because of lack of commercial interest?"

"I think people are afraid to attack the Right to Life lobby, that's all." Watson responded. "Screening is bad. Screening is Hitler."

But, countered Baltimore, genetic screening "is an opportunity for each *individual* to decide on for himself or herself."

Watson's response was that he finds it troubling that our society is indifferent to continued genetic disease. "There is a conflict between truth by revelation and truth by observation and experiment. I think the big fight eventually in our country is not going to be between Republicans and Democrats, but between those who think secularly and those who think in a fundamentalist way."

The audience applauded. "You know which side Caltech is on," said Baltimore.

"There are many people who believe in religion but don't want to restrict other people," continued Watson. "But fundamentalists want all people to follow their beliefs. People have had their lives totally set back by genetic disease, and I feel very strongly that we're failing ethically by not using the knowledge that we have."

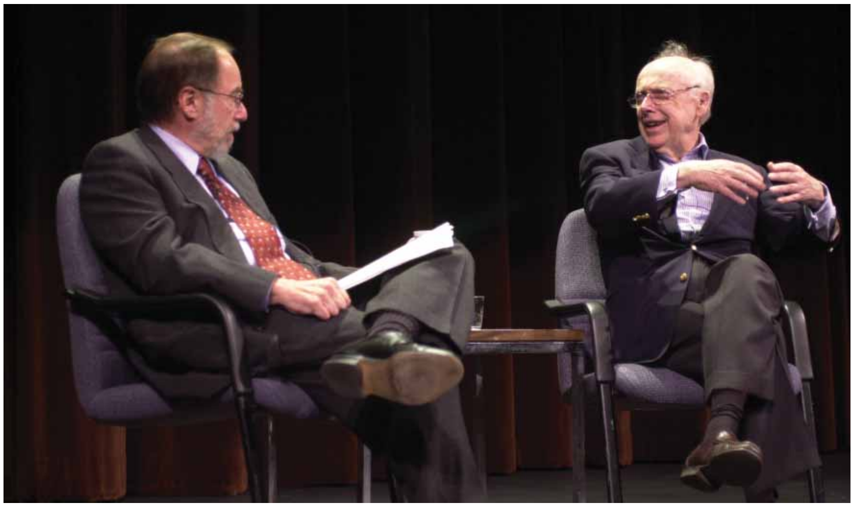
Baltimore observed admiringly that Watson had turned his question around, whereupon Watson quickly responded, to audience laughter: "You have less ability than I to say what you think."

After acknowledging that there was "truth in that," Baltimore changed the subject. He noted that 75 percent or more of the human genome is repetitive DNA. "There's a fish, the fugu, that has very little repetitive DNA, and it does, in its fishy way, live perfectly well. It has roughly the same number of genes as we have. Do you think," he asked, "that's a proof that all of that excess DNA really is junk, sort of a parasitic DNA that only cares about itself?"

"It's more like 95 percent," answered Watson. "As in the other species, it looks like there's about 5 percent that's conserved—1 percent are amino-acid-specifying, and the other 4 percent are useful in regulating when, where, and to what extent individual genes function." All human genetic variation resides in that 5 percent, he said, and he quoted Sydney Brenner's opinion that you would need to study only 30,000 humans to track it all down. "While many human attributes won't have genetic causes, we shall probably be surprised by the extent that they do."

Baltimore then brought up the Asilomar conference. "You and I have had very different opinions about the Asilomar conference," he noted. "We gathered together a group of people there [Asilomar is a conference center on the California coast near Monterey] in 1975 to consider whether recombinant DNA experiments should go forward untrammeled or should be developed in some orderly [i.e., regulated] fashion, because of the potential danger that recombinant DNA experiments might have. I must admit that they haven't shown any danger as time has gone along. I thought, and I still think, that that was a healthy process, even though nothing came out of it, but I know you feel differently."

Watson thought at the time that any regulation was capricious. He remembered that "Joshua Lederberg got up at the meeting and said, essen-



"You and I and all of our fellow scientists have to spend much more time with the public and do it over and over."

"If we could make mice more resistant to cancer, why wouldn't you want to have humans who were enhanced not to have so much cancer?"

tially, that if you regulate, people are going to think it's dangerous. And boy, he was right."

"There was no question that people overreacted," Baltimore conceded.

"You don't have traffic lights until there's an accident," added Watson. "Because so many things can go wrong. I really upset some people about genetically modified food. I said I thought they should instead worry about bicycles—worry about real things—because every time your kid gets on a bicycle, you don't know what the hell is going to happen. . . . At Asilomar, the difference between sounding good and doing good was ignored. We certainly sounded good, but when Maxine [Singer] and Paul [Berg] had that press conference and made the comparison to nuclear energy, I thought oh boy, we're in deep shit. We were."

"Well, we came out of it okay," admitted Baltimore. To which Watson responded, "We got out of it, but just by the skin of our teeth."

Baltimore: "Now we're into stem cells and cloning and genetic engineering, and I don't know what the next controversy will be. Biology simply is headline controversy these days. How bad do you think that is for the field?"

In his reply, Watson stated that he firmly believes that modern biology is beginning to profoundly affect how we as human beings live and think about ourselves. "You and I and all of our fellow scientists have to spend much more time with the public and do it over and over. We're finding out what human beings are, and most people don't think like us." He would like to see scientists run for Congress and become part of the government. "You've got to get in there. The Christian Right—they're in there. And we're not."

A question period followed with written questions submitted by members of the audience. Many of Watson's candid answers to these, as well as to Baltimore's questions, were prefaced by "I probably shouldn't say this" or "this will sound bad but it's probably true."

To a question as to why DNA is the only self-replicating biological code on Earth and what makes it so special compared to other self-replicating molecules that might be out there, Watson replied that "that's the sort of open-ended question for a chemist." Biologists, he said, were only interested in things that exist. Baltimore then put the question another way: "What if we found another whole start to life on Mars and there were at one time on Mars living organisms of a different origin than the origin in Earth?"

"It would be very interesting," answered Watson. "I would want to study it. I would be very excited."

One audience member asked, "Do you think genetically enhancing humans as opposed to just curing disease is reasonable?"

"If we could make mice more resistant to cancer," Watson answered, "why wouldn't you want to have humans who were enhanced not to have so much cancer? I think it's human nature to want to improve things. As someone of considerable Irish heritage, I can speak for this group. The Irish need improvement. . . . You know, when you say it this way, hell, we've all got a long way to go."

Asked what he thought were the prospects for treating human aging, Watson said he found Cynthia Kenyon's work exciting [Kenyon, at UC San Francisco, knocked out a gene in *C. elegans* that controls the aging process; the worms' longevity doubled and they remained healthy and active]. But Watson, 75, allowed that old people don't help society much. "Except for grandmothers," he added.

"But you're still writing books," said Baltimore, and then asked if Watson thought we would be using artificial means to increase longevity.

Watson: "Look. You don't want to die. I don't want to die. Spending money to increase our life span is human."

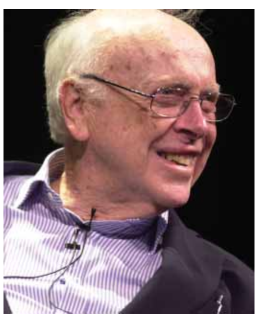
Watson's earlier discussion of a possible genetic basis for criminal behavior provoked a question on whether this would have a tremendous impact on criminal law.

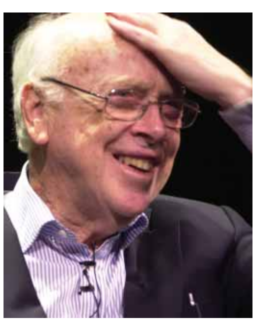
He agreed that it was a complicated problem and noted that humans aren't that different from chimps, who are born to kill—or from lions either. Watson said that he had been meaning to test himself on the suspicion that he might have "a low amount of the violence-promoting gene," but added that he had good parents and that nurture is immensely important. "That's why biology really is becoming so relevant. We have laws based on the fact that we're equal. And we're probably not going to be."

"So it is a big issue, having law that reflects the standards of genetics," commented Baltimore.

Watson: "And no easy solution."

The next question— "Were you genetically disposed to solve the structure of DNA?"—prompted laughter from the audience and an oblique answer from Watson: "Well, probably. I think curiosity is part of human nature, and I like facts more than most people." Watson went on to complain that too many of his former students lacked curiosity.





The Watson/Baltimore conversation can be viewed at http://atcaltech.caltech.edu/theater/.

Then Baltimore read the kicker to the question: "And if so, should you feel proud of your achievement?"

"Yeah, sure," said Watson, to more laughter. "Shouldn't John McEnroe feel good when he wins Wimbledon? Not everyone genetically programmed would be as good an athlete as he is."

Another question returned to the discovery of the double helix: "Do you think Rosalind Franklin would have shared the Nobel Prize with you and Francis, rather than Maurice Wilkins, if she had lived?"

Watson didn't answer directly, but noted that if they had given the double helix two Nobel Prizes, one in biology to Watson and Crick and one in chemistry to Wilkins and Franklin, "it would have been the *nice* thing." But the fact remains that it was Crick and Watson who had the insight. "It was very embarrassing to call Maurice up and say we've solved your problem. We didn't expect to get anything that big. We *did* use their data. It could have been done without the data, but we *used* their data."

But Franklin, he insisted, "made some wrong choices. She should have solved the structure early in 1952," but because she wasn't interested in building models and refused to accept the idea of a helix, she missed the significance of her X-ray picture—but Watson and Crick did not. He said that he originally wanted to call *The Double Helix*, his 1968 account of the discovery, *Honest Jim*, "because it raised the question: did we behave correctly? At that time we didn't even think about Rosalind; she was just holding things up. The person we wanted to beat was Linus.

"The English couldn't fail twice, so we had to win. Bragg would have been very disappointed," he said, referring to the ongoing competition between Bragg's Cavendish Laboratory and Pauling's group at Caltech.

Watson added that he was struck by the 18th-century Scottish philosopher David Hume's belief that humans are fueled by their passions, not by reason. "And Rosalind had a passion against helices, which overcame her reasoning." But Franklin wasn't alone in irrationality. Watson admitted, "I didn't want to use Chargaff's data. He was so unpleasant that I didn't want to use his data. That was passion. It had nothing to do with reason."

To a question about whether genetic engineering could be dangerous in the hands of terrorists eager to create bioweapons, Watson replied that terrorists don't really need it. If he were a terrorist, he said, he would use ordinary anthrax. "I worry about what exists."

"If you could change current science policy in the United States, what would you change?" In answer to this final question, Watson said he would give some government money to institutions to use at their discretion to "change this terrible situation where you can't get a grant till you're 35." This surprised Baltimore, who said: "You and I and lots of other people have spent years and years trying to educate the Congress *not* to give money to institutions, but rather to give it to individuals. I don't disagree with you that the perspective has changed, but it is a sea change to suggest that we now should give money to institutions."

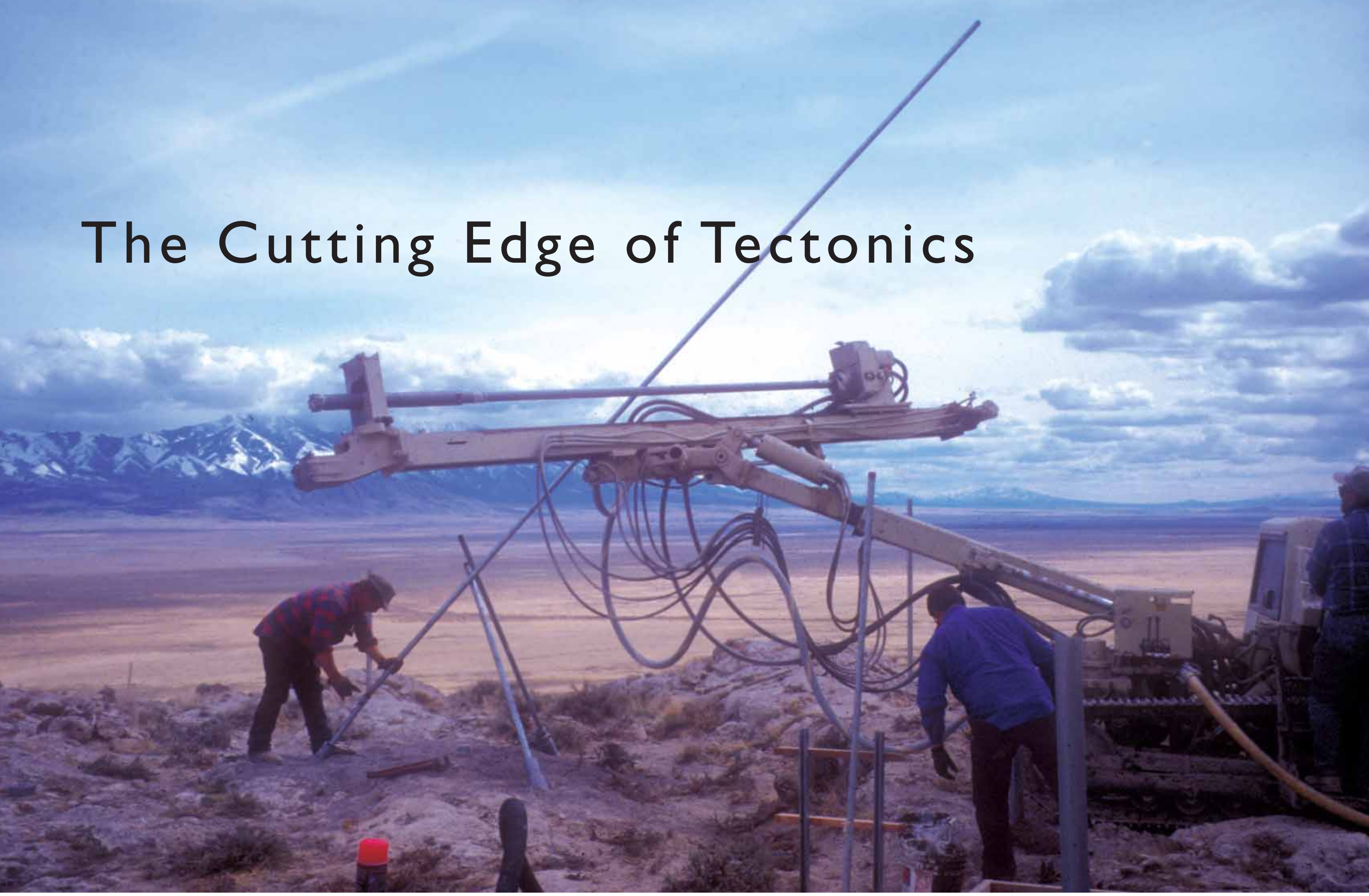
Although Caltech's initial greatness came from foundation money to the institution, things changed after World War II and the rise of government funding of science. "Forty years ago, there were relatively few people who ran science and determined its policy," said Watson. "And so the president of Caltech 40 years ago was far more important than you are today, relatively." (The audience, and Baltimore, laughed.) "Then there were only a few places that the country counted on to do it."

"Are you in a sense suggesting that science has gotten too big?" Baltimore asked. "There's too much? And so it's diluting quality or diluting good sense?"

No, answered Watson. "Understanding human beings at the molecular level—understanding the immune response, which is a lot more complicated than was thought 30 years ago, and the brain—will take an awful lot of people." He expressed confidence that scientists will make enormous advances in understanding the brain over the next 50 years.

Baltimore decided it was time to give his guest some respite before his next appearance that evening at Vroman's Bookstore. The audience thanked him for his Caltech visit with long and loud applause. □ *—JD*

The Cutting Edge of Tectonics



by Brian P. Wernicke

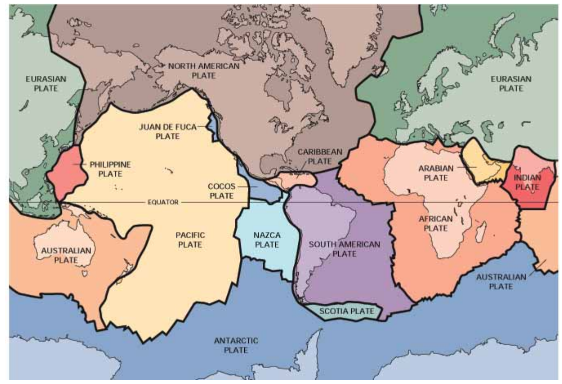
Installing a stable geodetic monument to hold a GPS antenna, above. Caltech has built a network of geodetic sites in the Basin and Range geological province of Nevada and Utah to measure the movement of this part of North America relative to the continental interior.

The term "tectonic" is often used as a metaphor for fundamental, unsettling change. Business analysts talk about "major shifts in the tectonic plates" of a certain market, or the "grinding tectonic shifts" of a recession. Most people don't think about the real thing very much, yet tectonic events like earthquakes and volcanic eruptions, with their associated tsunamis and mudslides, can wipe out tens or even hundreds of thousands of lives in just a few minutes. To match the death toll from the 1985 mudslide in Colombia triggered by the eruption of Nevado del Ruiz, or the 1999 Izmit earthquake in Turkey, the 9/11 bombers would have had to take down ten sets of twin towers, and to match that of the 1976 Tangshan earthquake in northern China, they would have had to level some 100 sets (at least 250,000 dead, just like that). The unspeakable horror of these disasters no doubt contributes to our tendency to keep them—and, by association, tectonics—out of sight and out of mind, except for the day they happen and perhaps a few weeks after. The contrast with plane crashes, terrorism, and even a run-of-the-mill homicide is our sense that tragedies caused by humans are somehow more preventable than those brought about by nature, even though the latter are far more devastating.

We can't eliminate natural disasters, but understanding them can equip us to bear them with comparative equanimity. In the case of earthquakes, a topic of great concern in Southern California, the better we can predict *what* will happen, even if not exactly *when*, the better we'll be able to take measures to mitigate the damage, with the peace of mind that we have not grossly underestimated or overestimated the danger. This is especially true of building codes, where over-design can be a very costly waste and underdesign deadly, and also of our insurance system, where the optimum level of investment requires a quantitative understanding of long-term risk. The construction and insurance industries might one day be so finely tuned that a magnitude 7 quake could occur in a city of millions with only a few dozen lives lost, and a total unexpected cost to society of perhaps a few hundred million dollars—as opposed to losses measured in thousands or tens of thousands of lives, as at Izmit, or in tens of billions of dollars, as with the 1994 Northridge earthquake. In the case of Northridge, our building

From the standpoint of public benefit, the question "When is the big one going to hit?" may not be so important, because as you'll see, it *is* going to hit. The really important question is "How big is big, and what do we need to do to cope with it?"

A dozen or so tectonic plates make up the earth's outer crust.

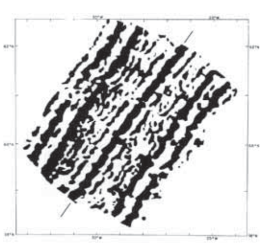


codes kept fatalities down to 61, but the harsh financial effects are still being felt by many of the uninsured. From the standpoint of public benefit, the question "When is the big one going to hit?" may not be so important, because as you'll see, it *is* going to hit. The really important question is "How big is big, and what do we need to do to cope with it?"

To understand tectonic hazards, we must understand the phenomena behind them. We already know a lot about why and how earthquakes occur, but we are now at a threshold where we can begin to understand them at a much more fundamental and useful level than ever before. The discovery of the theory of plate tectonics in the 1960s was geology's double helix, but just as knowing the structure and function of DNA has not cured cancer, understanding plate tectonics hasn't explained why earthquakes happen or volcanoes erupt, much less how big such events might be, and with what frequency they might occur. So what *is* plate tectonics, and what exactly is needed to take the next big step?

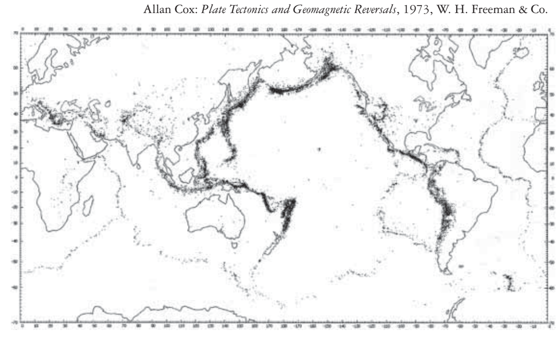
Plate tectonics is simply the observation that the outer part of the earth is composed of a relatively small number of internally rigid plates that float on a relatively weak, fluid substrate, and move a few inches a year in relation to one another. We know this because as the plates spread apart, they leave a precise record of how and where they were created. They're created at the midocean ridges, a huge system of mountains in the middle of the modern oceans that are volcanically active (*E&S* 2002, no. 3). For every kilometer that two plates move apart, a one-kilometer-wide, five-kilometer-thick batch of molten rock rises up from the mantle, cools, and solidifies to form new ocean crust. Particular mineral grains called magnetite within the newly forming rock align themselves parallel to the earth's magnetic field at the time of cooling, so each bit of new crust along the ridge carries a record of the direction of the magnetic field at the time it formed. We know that this field reverses on a million-year timescale, so as the plates spread apart, they function as a magnetic recorder that can be read by towing a magnetometer over the ocean's surface. Magnetic maps like the one bottom left show the history of reversals as stripes on the seafloor that look a lot like the bar code on an item you buy at the supermarket. Each of these stripes can be dated, because we know the times of the magnetic field reversals from studying rock strata that have accumulated on the continents, so by counting back from the midocean ridge, we can pin down precisely how the two plates on either side of a ridge moved apart through time.

The distribution of earthquakes across the globe also lends support to the theory of plate tectonics. Looking at the map below, it is immediately apparent that most of globe does *not* experience frequent earthquakes. The plates are basically stable, but there is deformation, manifested as earthquakes, where the plates are in contact at their boundaries, and there are also narrow, well-defined belts of earthquakes along the midocean ridges where the plates are moving apart.

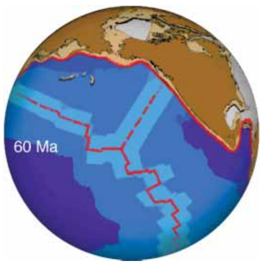


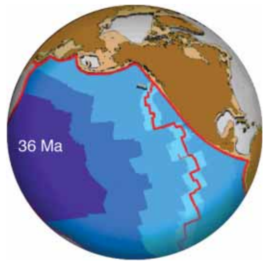
Allan Cox: *Plate Tectonics and Geomagnetic Reversals*, 1973, W. H. Freeman & Co.

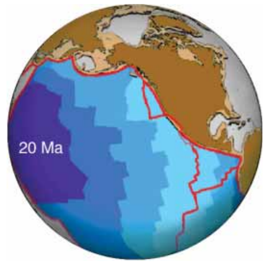
Allan Cox: *Plate Tectonics and Geomagnetic Reversals*, 1973, W. H. Freeman & Co.

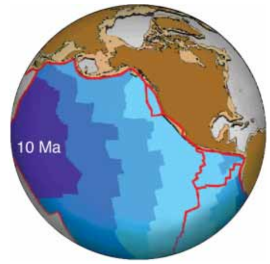


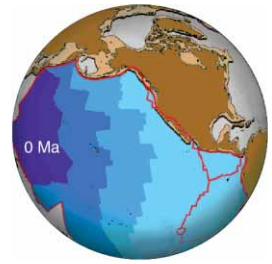
Global distribution of significant earthquakes between 1961 and '67, above. The ocean floor has been conveniently bar-coded with magnetic stripes, left. This magnetometer reading was taken at the Reykjanes Ridge south of Iceland.







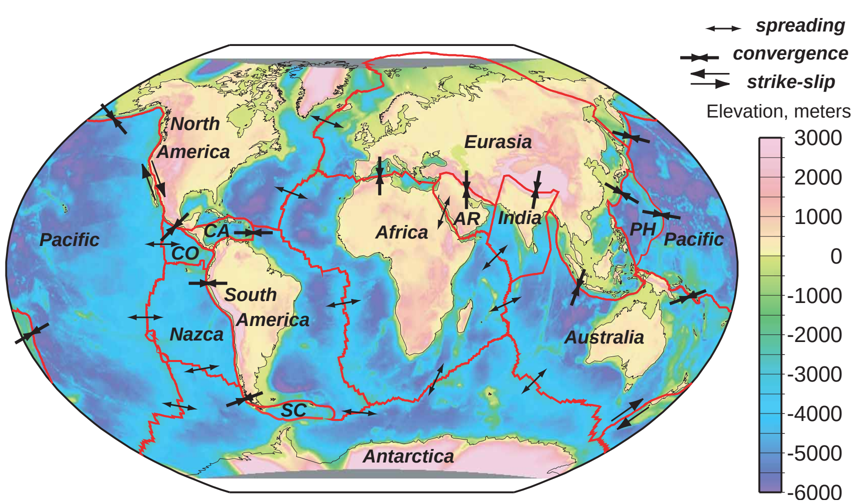




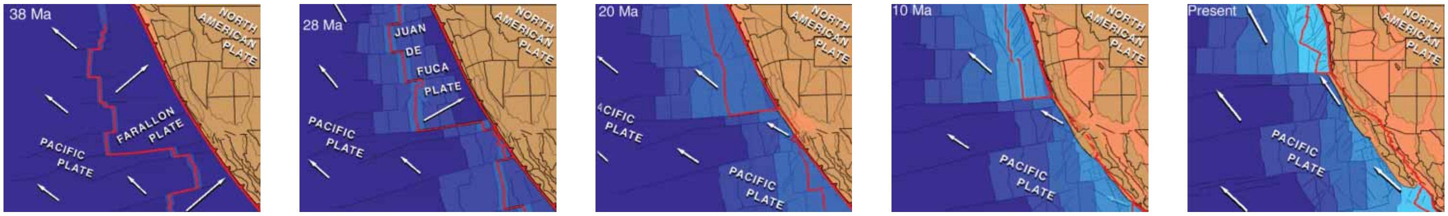
The modern picture of how the plates move with respect to each other is shown below. In addition to boundaries in the oceans where plates are spreading apart, there are places where plates slide directly past one another in a so-called strike-slip motion, and other places where plates converge. An oceanic plate often sinks back into the earth beneath a continental plate when the two meet, a process called subduction. And, as well as belts of earthquakes along each plate boundary, there are also belts of volcanoes. Along the mid-Atlantic ridge, for example, volcanoes and earthquakes are localized along the boundary between the North American and Eurasian plates (best observed in Iceland). Along the coast of Alaska, the Pacific plate plunges beneath the North American plate, creating large earthquakes such as the 1964 magnitude 9.2 Alaskan quake, and building a line of volcanoes on the North American plate stretching from the Aleutians to the interior of Alaska. In Southern California, the Pacific plate slides laterally past the North American plate, causing earthquakes on the San Andreas fault and on those faults beneath us in the L.A. basin.

We can now deduce quite accurately how the plates have moved over the last 200 million years by using the magnetic maps, as Professor of Geology and Geophysics Joann Stock (*E&S*, 1997, No. 3), and Professor Tanya Atwater of UC Santa Barbara, have done. The globes left and above are stills from Atwater's animation of the history of the Pacific Ocean plate boundaries from 80 million years ago to the present. The various shades of blue show the ages of the sea floor, with the lightest blue being the youngest. The Pacific spreading center created a lot of new plate, but the plate area created has been matched by the subduction of plates along the boundaries between the Pacific Ocean plates and North America. Plate motions like this are consistent with the global distribution of earthquakes and volcanoes—but knowing the motions doesn't predict that earthquakes and volcanoes should even exist. In fact the theory of plate tectonics doesn't predict anything other than the overall motion across the plate boundary, which as far as the theory is concerned could be a single, razor-thin, fault.

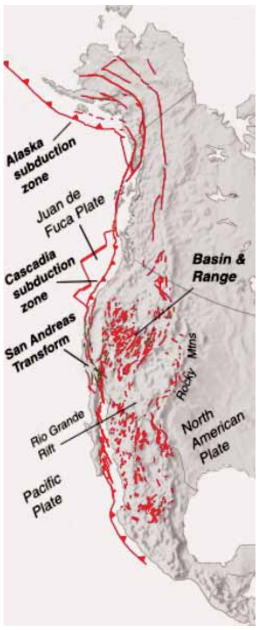
When we look in more detail at how plate boundaries evolve, especially where continents are involved, the picture becomes incredibly complex. For example, the plate boundary of western North America has a rather wide and complicated zone of faulting. Although some of these faults, like the San Andreas, clearly reflect the fact that the Pacific plate is moving northwestward at about five millimeters a year, the average rate of slip on



Above: Over the last 80 million years, the big spreading ridge in the Pacific Ocean added a lot of new (light blue) material to the Pacific plates and moved steadily closer to the North American plate. This animation, and the one at the top of the facing page, are at http://emvc.geol.ucsb.edu. Right: How the world's tectonic plates are moving in relation to one another.



Over the last 40 million years, the Farallon and Juan de Fuca plates have plunged below the North American plate, bringing the Pacific plate to the edge of the continent. Its movements since then have caused a lot of spreading (in pink) in the western part of the continent—just look at the growth of Nevada—and created the numerous faults shown in red on the map below.



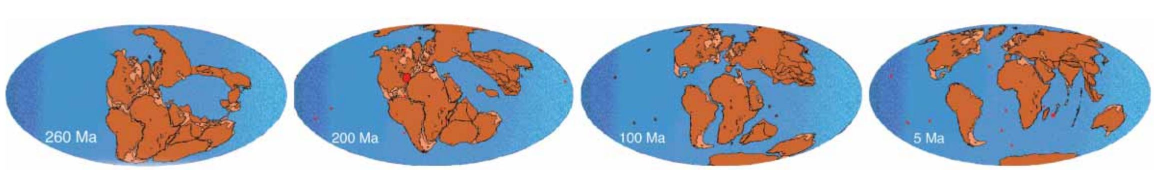
the San Andreas itself is only a fraction of the total plate motion, and the rest is soaked up by a complicated array of smaller faults (left). These include faults in Southern California that accommodate north-south convergence, called thrust faults, and faults across the Basin and Range province in Nevada and Utah that accommodate east-west stretching, called normal faults.

We can combine plate reconstructions with the geological history of the southwest to get a good picture of how this zone of faulting evolved, above. Over the last 40 million years, the ridge in the middle of the Pacific steadily approached North America. It collided with the continent between 10 and 20 million years ago, after which the boundary between the Pacific and North American plates widened, and the Pacific plate started to move obliquely away. This caused a huge area within North America to start spreading, creating the Basin and Range province of Utah and Nevada. Then, about 10 million years ago, the Pacific plate began to move more parallel to the coast, giving birth to the strike-slip San Andreas, tearing Baja California off the edge of the continent and driving it northward into the San Andreas, and creating the thrust faults in Southern California.

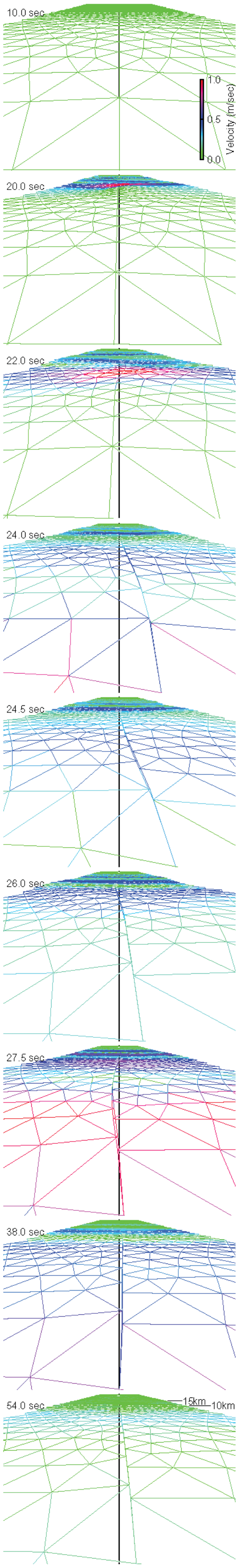
But, as I said earlier, plate tectonics is only a theory of motion, like Kepler's description of the solar system, and cannot be used to predict why there are earthquakes, how often they will occur, how big they will be, and why patterns of faulting along continental plate boundary zones are so wide and complicated. We need a theory of how motion is related to force, analogous to Newton's laws. In particular, we need a physical theory to account for both the slow, steady motion of plates on the one hand, and the rapid, nonsteady behavior of earthquakes on the other. There is reason for optimism that we can do this by using new methods of observation that bridge the huge gap in timescale between the two types of behavior.

To understand why plates move in the first place, it's helpful to take a really long view back. The earth formed about 4.5 billion years ago, yet the oldest magnetic stripes on the ocean floors are only about 200 million years old, which implies that if plate tectonics in its current form has been active through most of the earth's history, about 25 completely new oceans must have been created and destroyed. In the reconstruction of the history of the earth over the last 260 million years as based on plate tectonics (bottom), you can see that the continents were once assembled in one large, vaguely C-shaped mass known as Pangaea. Over the millennia, chunks were transferred from the southern part of the C-shape to the northern part (which eventually became Asia), and each time a piece was transferred a new ocean basin opened in its wake. There were also periods when huge volcanic eruptions poured out magma from the mantle. In a little over 200 million years, a lot of crust rose up, and a lot sank back down. In terms of physical theories that relate force and motion, we have a very good idea that what drives this is heat transfer from the interior to the exterior of the earth through a process called convection.

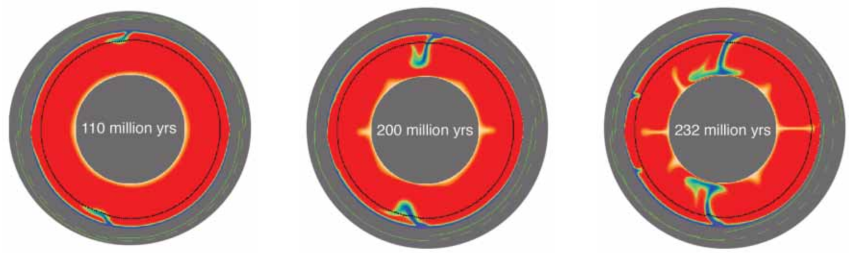
J. Besse & V. Courtillot: *J. Geophys. Res.*, 107, B11, art 2300 (2002)



Some snapshots of our planet at various times in the past, based on plate tectonics. A movie of this (and one showing how the landmasses will regroup in the future) can be found at http://www.ipgp.jussieu.fr/anglais/rub-terre/surface/time.html.



Left: Model of an earthquake on a strike-slip fault. The initial position of the fault is represented by the line down the center. Just behind the wave of strong ground motion, the fault swings rapidly from side to side until, 24 seconds after the start, it slips, and the horizontal lines crossing it break and realign. This all happens very quickly—the fastest waves are traveling at 3 feet a second. Below: Lava lamp earth.



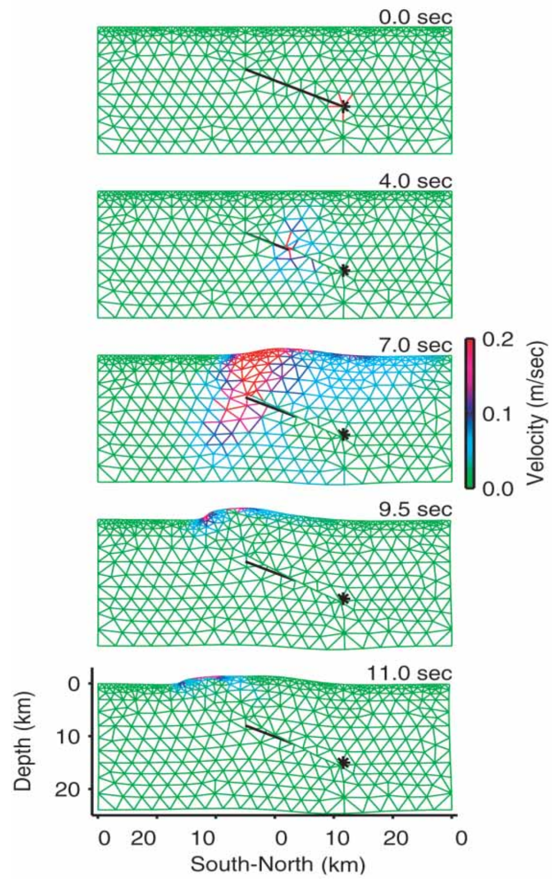
The same thing happens when water is boiled on the stove—the water sits still in the kettle as heat is added, but there's a point when the water at the bottom starts to rise up because it is hot and buoyant, and the cold water at the top sinks down because it is relatively dense. Lava lamps work on the same principle. In the model of convection in the earth's mantle developed by Professor of Geophysics Mike Gurnis and colleagues, above, the relatively cold, blue material represents subduction, the red material is intermediate in buoyancy, and the hot, yellow material is very buoyant. As the cold material sinks, hot material rises from the boundary between the mantle and the earth's molten iron core. (The full animation can be seen at http://www.gps.caltech.edu/~gurnis/Movies/movies-more.html.)

These examples show that we have the computational firepower to develop models of long-term processes such as plate motion, and that we can even make detailed models of individual plate boundaries. The timescales of these are in millions of years. In comparison, similarly sophisticated physical models developed by Brad Aagaard, of the USGS, and Tom Heaton, professor of engineering seismology, have timescales in seconds. Some stills of their animation of an earthquake on a strike-slip fault like the San Andreas (where one block suddenly moves horizontally relative to the other) are shown on the left. Such models of how the ground will move in response to a quake on a given fault help us to predict the worst of the shaking, or strong ground motion, of the earthquake, which is exactly what engineers need to know when designing buildings.

The challenge lies in bridging the gap between two sets of models with a difference of 13 orders of magnitude in time. The part of the spectrum we don't understand very well, mainly because we have very few observations, is the time ranging from decades to hundreds of thousands of years. If we can fill in this gap, we may be able to construct seamless physical models of how plate motions cause earthquakes, which in turn could give us a much better handle on answering questions about the frequency and strength of damaging quakes—the questions that matter most to society. New, improved ways of seeing where faults are, how often earthquakes occur on them, how fast they are moving, and how they moved in the past, make me optimistic that we can do it.

We cannot really understand the hazards of living in areas prone to earthquakes if we do not know where all the faults are. Many faults that generate large earthquakes don't rupture the surface cleanly when they move, and this is nowhere better demonstrated than beneath metropolitan Los Angeles. John Shaw at Harvard and Peter Shearer of the Scripps Institution of Oceanography studied the area around the 1987 magnitude 6 Whittier Narrows earthquake, and found a large blind-thrust fault. The red and white "beach ball" in the map below left on the facing page shows the epicenter of the quake, and the purple line down the middle shows the profile along which a seismic crew vibrated the ground with big trucks, listening carefully to the waves that bounced back in order to get an idea of the structure of the earth at depth. The green circles show oil and gas fields, and the blue lines are the depth contours of a large fault plane that was found. The cross section of this area (facing page, bottom center) showed that at the surface the sedimentary layers were flexed and folded, but deeper down, a group of reflections, shown in red, broke up the sedimentary layers along the line of the fault. This type of fault dies out upward, and has younger sedimentary layers draped over the top, so it's almost impossible to see at the surface. The fault plane lined up extremely well with the main rupture and aftershocks of the Whittier Narrows quake (facing page, bottom right), which must have been due to this thrust fault. With the fault's geometry known, a model of the type of

Airborne Laser Swath Mapping stripped bare the wooded Toe Jam Hill area of Bainbridge Island to reveal a prominent east-west fault line running across the top. The vertical stripes were scoured by glaciers.

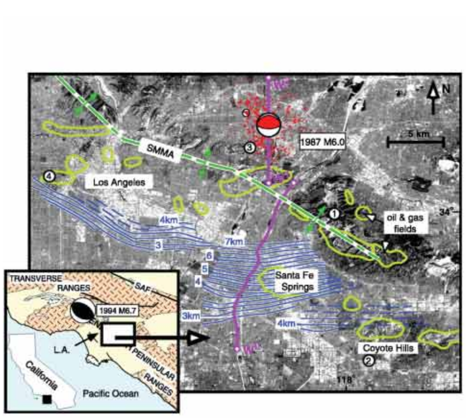


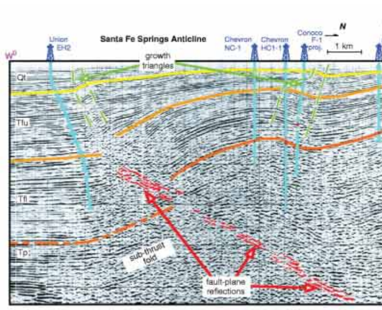
Above: In this model of an earthquake on a blind-thrust fault, the strong ground motions rush to the surface, where they crest like an ocean wave. Bottom, left to right: Seismic recordings taken at Santa Fe Springs, an area south of the 1987 Whittier Narrows earthquake (epicenter shown by the red and white "beach ball") revealed a blind-thrust fault hidden below ground (middle diagram), with the same strike and dip as the fault that ruptured in the Whittier Narrows quake, right.

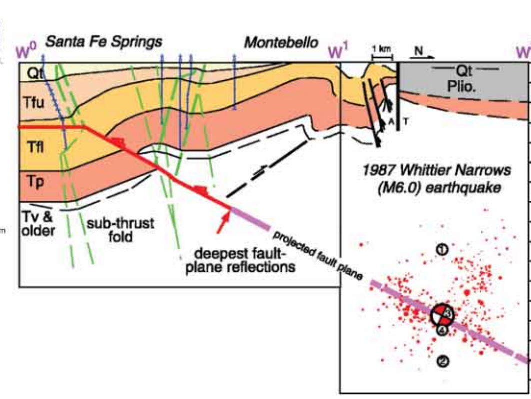
shaking it might deliver was constructed, left. You can see that the rupture starts at depth, and moves up the fault plane in a wavelike fashion—faults like these are particularly dangerous because large vertical accelerations, reminiscent of an ocean wave, are generated near their upper tip, and these can be very damaging to buildings. Many built-up areas of the L.A. basin could be on top of such hidden faults.

Even if faults *do* break the earth's surface, they can be very difficult to find, especially in areas covered with thick vegetation, like the Pacific Northwest. But a new technology called Airborne Laser Swath Mapping (ALSM) can image vegetated areas and return fine-scale topographic profiles that filter out reflections from the vegetation, enabling the creation of so-called "bald earth images." In the Toe Jam Hill area of Bainbridge Island in Puget Sound there was nothing obvious, either in aerial photos or when walking around on the ground, that suggested the presence of a fault. But ALSM revealed a scar across the north side of the island that turned out to be a strand of the active Seattle fault system.

Once we figure out where the faults are, we need to know how often they break. The times at which large earthquakes occurred on part of the



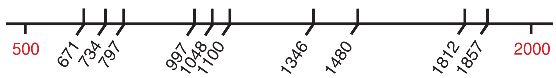




Shaw, J.H. & Shearer, P.M.: *Science* 283, 1516 (1999)

Near right: Dates of earthquakes on a section of the San Andreas fault close to Caltech. Far right: Over the last 26,000 years, earthquakes pushed the Wasatch Range up behind Salt Lake City. Each step in the graph represents one earthquake.

San Andreas fault have been determined by Sharp Professor of Geology Kerry Sieh and colleagues using carbon-14 dating. They found that over the last 1,500 years, the fault running along the southern margin of the Mojave Desert near Palmdale has ruptured 10 times, with an average frequency of about once every 150 years. The earthquakes have not been at all regular, but have occurred in clusters, with as little as 52 years

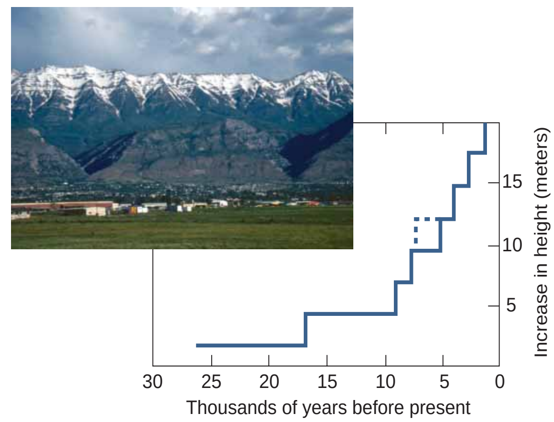


K. Sieh & S. LeVay: *The Earth in Turmoil*, W. H. Freeman & Co.

between some events, and as much as 332 years between others. Are we due for another one soon? Tough to say, but given this history it would not be anything like a surprise if one were to occur before you finish reading this article.

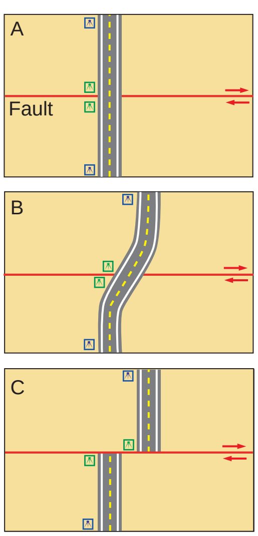
Jim McCalpin (of GEO-HAZ Consulting, Inc.) and colleagues have determined both the time of faulting *and* the amount of upward displacement of the mountains that occurred due to each event for the Wasatch normal fault in Utah. The Wasatch Range is being displaced upward relative to Salt Lake valley to accommodate the east-west stretching of the Basin and Range province. Looking at the plot left, which shows the upward motion, it can be seen that some six earthquakes have occurred in the last 9,000 years, giving a total upward movement of 16 meters (about 50 feet). In contrast, between 26,000 and 9,000 years ago there was only one earthquake, with a total motion over that time of only 3 meters (10 feet). It would appear that the region may be in the middle of a very busy period at the moment!

One way to try to understand how the past links with the present is to get a firm idea of how fast the blocks on either side of a fault are moving at present, using the techniques collectively known as geodesy. The concept is pretty simple. Faults tend to slip mainly during earthquakes, but in between these quakes the crustal blocks on either side of the fault continue to move very slowly and steadily. The regions of each block closest to the fault, however, are stuck—locked in place by the fault—and absorb energy through the accumulation of strain in the rock, much as a spring absorbs energy when extended or compressed. Using geodetic methods like the global positioning system (GPS), we can track the motions of points on either side of the fault to measure how fast this energy is building up. The greater the energy, the

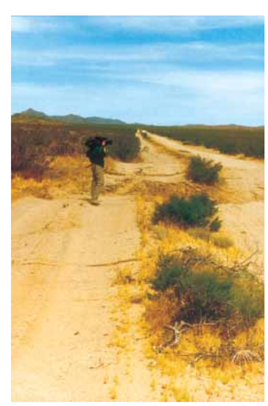


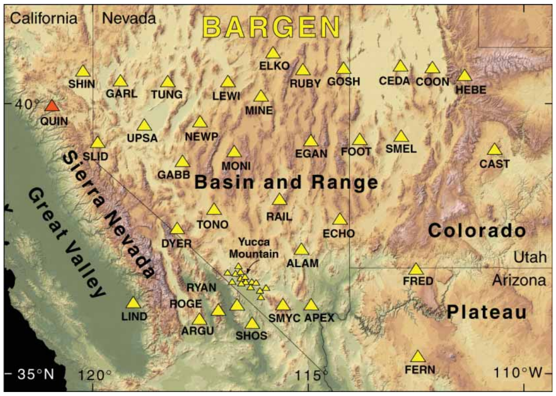
closer the fault is to failure. In the diagrams left, the blue GPS sites 20 kilometers from the fault move at a fairly steady rate just like the plates do. But the green sites close to the fault (about a kilometer away), where strain energy is building up, don't move as much, and the locked fault does not slip at all. When the next earthquake happens, the fault slips so as to line up the green sites with the blue sites again. When this happens, the strain energy built up in the crust is converted to heat and, regrettably, to the energy of seismic waves radiating through the crust. So the steadily moving geodetic sites see little or no motion during the earthquake, while sites closer to the fault feel a sudden jerk.

Over the last 10 years, a number of workers have built GPS-based geodetic networks around the world with the aim of seeing how things are moving. One example of a network of sites built by

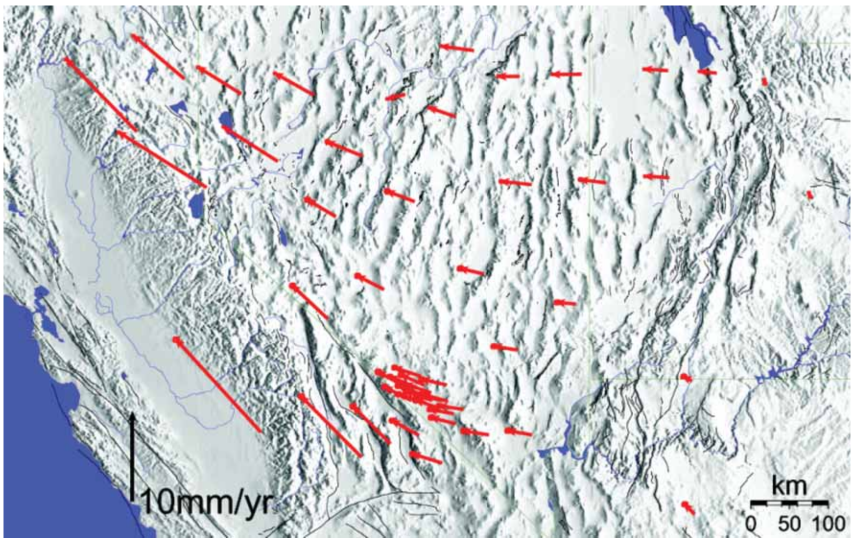


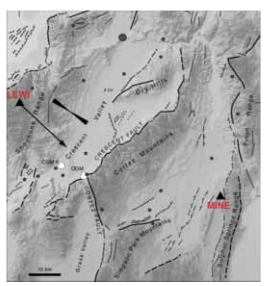
Left: A road with GPS sites along it is built across a strike-slip fault immediately after an earthquake (A). Red arrows show the direction the tectonic plates are moving. After a few years (B), the plates have moved quite some way past each other, taking the blue GPS sites with them. The green sites have moved apart much less, because the land they're on is locked by the fault. Eventually, there's another earthquake (C), the road is displaced, and the blue and green sites realign in one sudden jerk. This happened to the road in the photo, right, taken just after the '92 magnitude 7.3 Landers earthquake. The NBC news cameraman is standing in front of the fault where it crosses the road, which has been offset to the right on the far side.





Wernicke, B. et al.: *GSA Today*, November 2000.



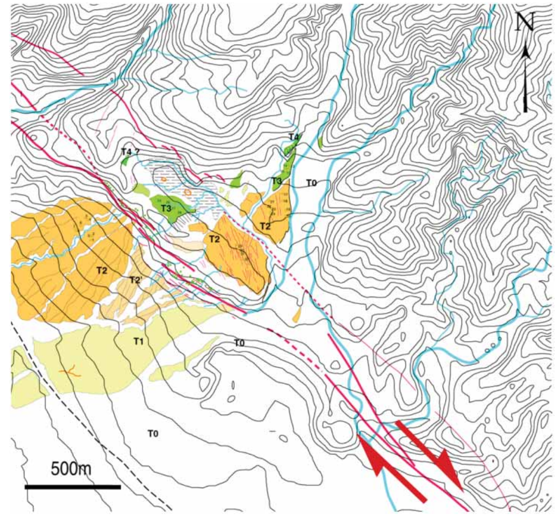


Top: Map showing the location of GPS sites in the BARGEN network. Above: The red arrows show the direction and rate at which each site is moving in relation to the center of the continent. Right: An oddity—site LEWI is moving toward MINE rather than away from it. Below: A typical GPS site in the BARGEN network.

Caltech is called the Basin and Range Geodetic Network, or BARGEN, where a GPS antenna mounted on an ultrastable monument has been erected at each site (left). We drill one vertical borehole and three slanting ones into the bedrock to a depth of about 30 feet, then slip steel posts down the holes (which is what we're doing in the photo on the front page of this article), grout them to the earth between 15 and 30 feet deep, and isolate the posts from the upper 15 feet of earth with foam-padded casing. The tops of the posts are welded together, and a GPS antenna is set on top, while a weatherproof box nearby houses the GPS receiver. This network has been in place since the late 1990s, recording the east and north components of motion. GPS can estimate position in this way to within about one millimeter each day, which means we can measure the relative rate of motion or velocity of any two sites to within a fraction of a millimeter a year. We use this information to make maps like the one on the left, of the direction and rate of movement of the geodetic sites. The red arrows, or vectors, show the velocity of the network relative to the interior of the North American plate. The size of the arrows increases steadily from east to west, indicating horizontal extension of the crust in the Basin and Range region. Then the arrows twist around, showing northwest motion in the region of the Sierra Nevada, as the sites begin to feel the northwesterly shearing strains associated with the San Andreas fault near the coast. There's an interesting exception to the pattern in north-central Nevada, where one site is moving much more slowly than the one directly to its east. Site LEWI is moving *toward* site MINE, which seems odd in a place like the Basin and Range where the crust is pulling apart on normal faults, not getting smashed together on thrust faults as in the Los Angeles basin. Between the two sites is a major normal fault, the Crescent fault, which is of the type that causes horizontal extension, in this case extension in exactly the same direction as the GPS results are telling us there is compression, northwest to southeast. Postdoc Anke Friedrich, now at Potsdam University in Berlin, has shown that the last major earthquake on this fault happened 2,800 years ago, so until that time sites LEWI and MINE must have been moving apart, to accumulate the strain that leads to an earthquake. Assuming the Basin and Range is generally an area of horizontal stretching, the faults between the two sites must now be *losing* strain energy, and accordingly will be much less likely to fail than faults nearby.

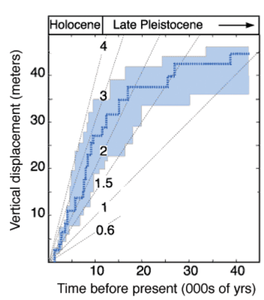
This example—and there are others like it—show that our simple idea of the seismic cycle has some major deficiencies. There appear to be processes at work on the decadal to millennial timescale that we are only just beginning to think about, as we start to understand the motions that occur at timescales longer than the earthquakes themselves and their immediate aftermath. Although highly

Cosmogenic nuclide dating enabled geologists to work out that the Biskra alluvial fan near Palm Springs, highlighted in orange, was formed by an ancient river 32,000 years ago. Between then and now, the San Andreas fault (red lines) has offset the lower part of the fan by an average rate of 22 millimeters a year.

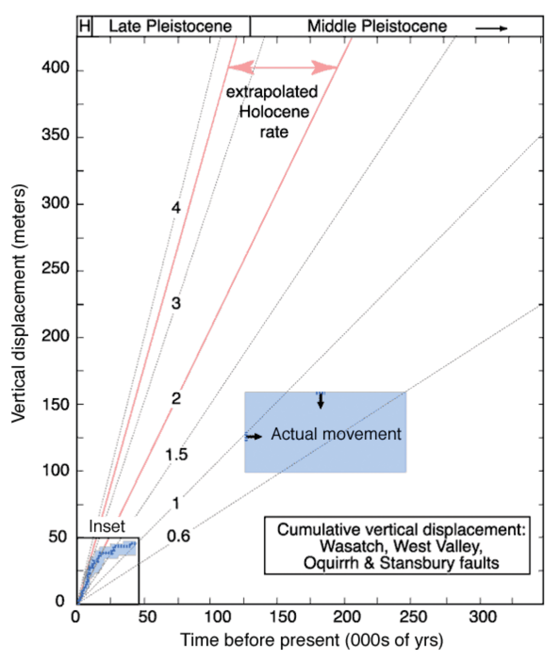


accurate geodesy is part of the solution, we must also get a handle on how fast faults moved in the past. In general, we have only been able to date active fault motions accurately to the maximum age limit of carbon-14 dating, and then only in places where we could recover charcoal or other carbonaceous material. Faults like the San Andreas usually offset features in the landscape such as river channels and the sides of alluvial fans. Up until the mid-1990s, the surface of the offset alluvial fan near Palm Springs (above) would have been impossible to date, because it had no charcoal on it—and even if it did, its age might be well outside the range of precise carbon-14 dating. But a new dating method has recently become practical, based on the fact that very infrequent cosmic rays—generally neutrons—hitting the outer few centimeters of the earth's surface cause nuclear reactions in exposed rocks that produce distinctive isotopes of common elements called cosmogenic nuclides. These nuclides can be measured to determine how long the rock has been near the surface—think of it as measuring the rock's suntan. The method works over a time span of several thousand to a few hundred thousand years, whereas precision carbon-14 dating is limited to 30,000 years or less. Based on its cosmogenic nuclides, the Biskra alluvial fan formed about 32,000 years ago, while its offset shows that the average rate of movement of this part of the San Andreas has been about 22 millimeters a year over that time span. This method will make it possible to observe a broad range of average motion rates across most continental fault zones, contributing richly to filling in the gap between measurements at human and at plate-tectonic timescales.

One place where we are getting a glimpse of the transition from earthquake cycles to plate-tectonic timescales is the Wasatch region, where we have tentative ages for Wasatch fault movements covering the last 250,000 years. The graph on the far left shows the vertical displacement rate versus time for the Wasatch and two neighboring faults over the past 40,000 years, and the graph left compares this rate with an estimate of movements over the last 250,000 years. On average, these are very slow compared with recent rates, especially the rapid rates since 10,000 years ago.



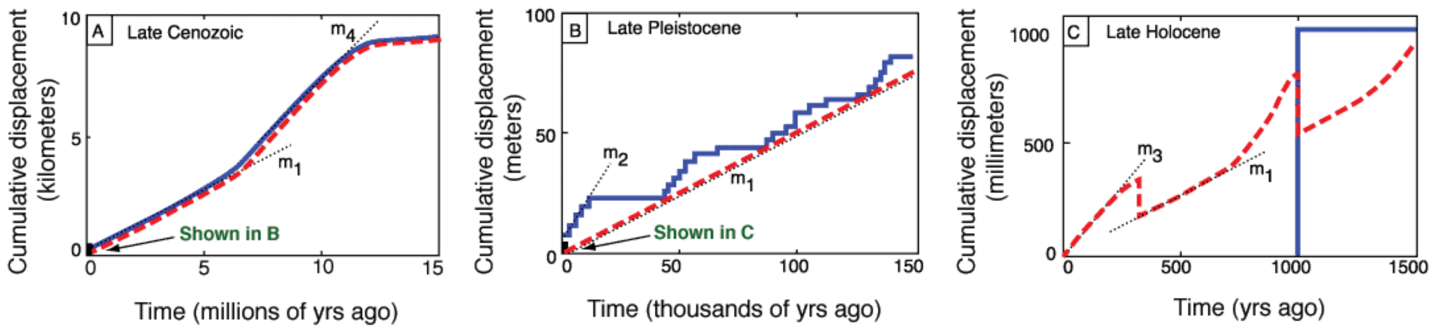
Friedrich, A. M. et al., *J. Geophys. Res.*, 108, B4 (2003)



Far left: The rise in height over 40,000 years of the Wasatch fault and two others. Extrapolating the rate of increase in height calculated from this plot farther back in time, left, gives an overestimate of the rate of upward movement over the last 250,000 years (red lines). The actual rate of movement is shown by the blue box.

Mountain building in the Wasatch region viewed over three different timescales. The blue lines are changes in geological height, and the red dashed lines show geodetic motion. B is an enlargement of the lower 1/1000th of A, and C is the lower 1/1000th of B. In C, the blue line shows that there has only been one earthquake over the last 1,500 years, but the stepwise rise in geodetic motion shown by the red dashed line could be caused by other faults nearby.

Friedrich, A. M. et al., *J. Geophys. Res.*, 108, B4 (2003)



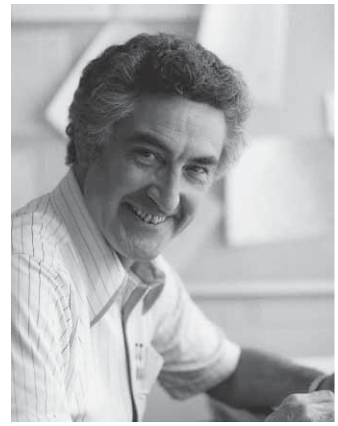
Putting it all together, we can see the motion history across a millionfold difference in time. Kilometers of motion on the fault observed over millions of years (top left) show that there has been a general slowing of the average rate of motion since about 10 million years ago. The middle graph—the one we are most eager to fill in—looks at motions measured in meters over a few hundred thousand years. We're speculating that the geodetic rate may be rather smooth, but the earthquake strain release might be periodic, occurring in clusters every twenty to forty thousand years or so. If this is the case, what is it trying to tell us about the physics of how earthquakes really work? In the righthand graph, motions of millimeters or centimeters over hundreds or thousands of years are shown, but our knowledge of this is also incomplete. Here we see the strain accumulation between earthquakes, sudden jumps from nearby earthquakes, and large jumps from earthquakes on the fault nearest to the geodetic site.

The scientific community is presently gearing up to make observations on these timescales, and to develop models that explain the observations. EarthScope, a $200 million National Science Foundation initiative to investigate the structure and evolution of the North American continent, includes the installation of some 900 new GPS stations— similar to those in the BARGEN network—across the Pacific–North America plate boundary zone, which will yield an unprecedented view of active plate-boundary strain. Caltech itself is in the final planning stages for a "tectonic observatory" within the Division of Geological and Planetary Sciences that will focus on key plate boundaries around the globe. Using cosmogenic nuclide dating and other methods, we'll begin to unravel how different faults contribute to the evolution of plate boundaries in the way we've already started to do for the San Andreas and Wasatch faults.

With these and other data coming online over the next decade, we will be able to see in some detail the long-term behavior of plate boundaries, which should help us take the next big theoretical steps in understanding the physics of fault systems and earthquakes. I expect these advances to greatly improve our ability to determine the "tectonic climate" of the globe, and to help us make a realistic assessment of the measures necessary to cope with tectonic hazards. The famous dictum of Will Durant, "Civilization exists by geological consent, subject to change without notice," might then more aptly conclude "subject to change with all due notice." □

Chandler Family Professor of Geology Brian Wernicke, a native of Los Angeles, gained his BS at USC in 1978 and his PhD at MIT in 1982. After a year as an assistant professor at Syracuse University he joined Harvard, where he rose to associate professor in 1986, and full professor the year after. A year at Caltech as a visiting professor in 1990 was followed two years later by a more permanent move back to the action along the Pacific–North America plate boundary, to take up a professorship in geology. The plate boundary welcomed him with a magnitude 7.3 earthquake at Landers. Wernicke received a Presidential Young Investigator Award in 1985, and in 1991 he both received the Young Scientist Award of the Geological Society of America, the Donath Medal, and was elected a fellow of the society. He is married to another Caltech geologist, Professor of Geology and Geophysics Joann Stock. This article has been adapted from a Watson lecture given in May 2003; you can watch the entire lecture at http://atcaltech.caltech.edu/theater.

PICTURE CREDITS: 27 – USGS; 28, 29 – Tanya Atwater; 28 – Joann Stock; 30, 31 – Brad Aagaard, Tom Heaton; 30 – Shijie Zhong, Mike Gurnis; 31 – Puget Sound LIDAR Consortium; 32 – Jim McCalpin, GEO-HAZ Consulting; 34 – Kerry Sieh



Al Hibbs 1924 – 2003

Albert R. Hibbs, BS '45, PhD '55, known worldwide as "the voice of JPL," died on February 24 at age 78 of complications following heart surgery. Born October 19, 1924 in Akron, Ohio, Hibbs decided as a five-year-old that he wanted to go to the moon. He *did* qualify as an astronaut, in 1967, even though he was seven years over the age limit. He was slated to fulfill his dream on Apollo 25, but the program ended at 17. At Caltech, he studied physics under the Navy's V-12 program. "I wanted to conquer space, and my roommate, Roy Walford, decided that he would conquer death. Together we would then conquer time," he later wrote. (Walford, now professor emeritus of pathology at UCLA's medical school, is an internationally known gerontologist.) In the late 1940s, he and Walford took time off from graduate school at the University of Chicago to "break the bank" in Reno and Las Vegas by exploiting the mechanical quirks of certain roulette wheels, earning them a story in *Life* magazine; their winnings financed a 40-foot sailboat and a year and a half roaming the Caribbean.

A backstage photo of Hibbs as a fishmonger and fellow JPLer Bruce McLaughlin (BS '77) as Motel the tailor in Caltech's February 1980 production of *Fiddler on the Roof.*

Hibbs joined the Jet Propulsion Laboratory, then run by Caltech for the Army, in February 1950. (The Lab was developing guided-missile technology but the word "rocket" smacked too much of Buck Rogers, so Caltech had coined the euphemism to avoid scaring off potential donors.) As head of the Research and Analysis Section, he was the systems designer for America's first successful satellite, Explorer 1.

When JPL became part of the patrimony of the newborn NASA later that year, he helped draw up JPL's master plan to explore the solar system with unmanned spacecraft. His gift for explaining difficult science in lay terms led to him becoming the radio and television chronicler of the Ranger and Surveyor missions to the moon in the 1960s; the Mariners to Venus, Mars, and Mercury in the '60s and '70s; the Vikings to Mars in the '70s; and the Voyagers to the outer solar system in the '70s and '80s. He also hosted or narrated various programs for NBC and PBS, winning a Peabody in 1963 for the four-year NBC children's series, *Exploring*.

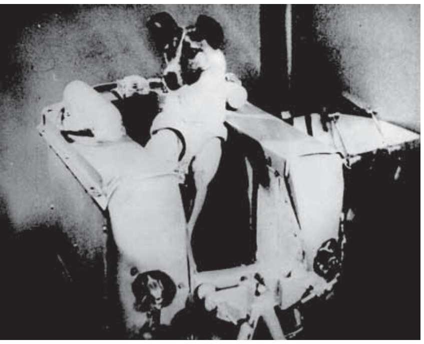
After helping to set up JPL's Space Science Division from 1960 to 1962 and serving as its first chief, Hibbs went on loan as a staff scientist for the U.S. Arms Control and Disarmament Agency, studying how arms-control treaties could be monitored from space. Five years later, he returned to JPL, where he spent the rest of his career working in a variety of technology programs, earning NASA's Exceptional Service Award and the NASA Achievement Award in the process. He retired in 1986, three years before Voyager 2 reached Neptune.

Hibbs maintained close ties with Caltech, where over the years he taught courses in government, national security, transportation issues, and physics. He took time off from JPL to earn his PhD, supported by his wife, the late Florence Pavin. His advisor was Richard Feynman, another noted raconteur, lockpicker, and thespian, and the two became close friends. They cowrote *Quantum Mechanics and Path Integrals*, a standard text on the subject, and Hibbs wrote the foreword for *Surely You're Joking, Mr. Feynman*.

Hibbs's own unpublished reminiscences, taped by Nicolas Booth, are the source for the account of Explorer 1's launch that follows.

Hibbs is survived by his second wife, Marka; children Victoria and Bart (BS '77); stepchildren Larry Wilson and Alicia Cortrite; sister Agnes Jones; and three grandchildren. Donations may be made to the Caltech Y, Mail Code 158-86, Pasadena, CA 91125. □—*DS*

On the Edge of Space by Al Hibbs



Sputnik I, launched by the Soviet Union on October 4, 1957, inaugurated the Space Age and scared the bejeezus out of America. The basketball-sized, 183-pound object passing over our heads once every 96 minutes was a reminder that nuclear bombs could ride on rockets as well. This fear turned to outright terror on November 3, when the half-ton Sputnik II was launched, carrying a dog named Laika, above. Unfortunately, the first Earthling in space had a one-way ticket and died when her oxygen supply ran out a week later.

It was the last Friday of January 1958, and I stood in the gathering gloom of a Florida night outside a small Quonset hut on a windswept sandspit that nobody had ever heard of called Cape Canaveral. America was trailing badly in the Space Race—then just a few months old, during which time the Soviet Union had launched two Sputniks, and our first attempt, Vanguard, had blown up on the launchpad live on television. That had been a Navy project. At the Jet Propulsion Laboratory, we were a contractor to the Army and we didn't want to suffer an equally ignominious episode. I was just 33 years of age.

After Vanguard's failure, a number of politicians complained that we had got the wrong Germans. (After World War II, we had scooped up quite a number of engineers who had worked at Peenemünde on the V-2, the world's first ballistic missile.) In fact, we had got the cream of the crop, led by the redoubtable Wernher von Braun. They were now at the Army's Redstone Arsenal in Huntsville, Alabama. There were so many Germans there that some of the Army people used to refer to it as Hunsville.

Although the Navy had been given the plum job of launching America's first satellite with Project Vanguard's approval back in 1955, the Army had never given up. We called our project the "Reentry Test Vehicle" or RTV, which we claimed was going to test the nose cone for the Army's Jupiter intermediate-range ballistic missile. We'd go well above the atmosphere—we had enough power to do that—then point straight down and aim at the earth. This would mimic the Jupiter' reentry conditions. We tested it three times, and I recall someone suggesting that we deliberately have a failure—that is, the object we were firing into space would fail to reenter and just stay up there. It was a nice idea!

The Navy knew perfectly well what we were up to, even though the general public didn't. When a local newspaper in Huntsville picked up those innocuous initials and suggested that they stood for "Rocket To Venus," there was an almighty row. It started off a congressional investigation and ended up with us having to hide what would become the first experiment in space in a cupboard at JPL. Eventually, President Eisenhower came to our rescue, appearing on television to announce that he was asking the Army to attempt the launch of a satellite as part of U.S. participation in the International Geophysical Year.

While all this was going on, the head of the Naval Research Laboratory, Admiral Bennett, got up in the midst of a meeting of the Joint Chiefs of Staff and complained that the Army should not be given the job. He felt the Army's launching system was unreliable. The Joint Chiefs were very annoyed, as this was not on the agenda, so they directed him to get together with the Army's chief scientist—a guy named Jones—to discuss the matter.

So a JPL group showed up in Mr. Jones's fancy Pentagon office—walnut table and leather-upholstered furniture. I was there because I had done all the calculations on the probabilities of success and failure. There was also Bill Pickering [BS '32, MS '33, PhD '36], the Lab's director; and Jack Froehlich [BS '47, MS '48, PhD '50], the project manager. Our opposite numbers also showed up. There was Dr. Hagen from the Naval Research Laboratory, head of the Vanguard project; Bennett; and sitting off to one side another admiral named Clark, who was Bennett's superior in the Office of the Chief of Naval Operations.

Jones opened the meeting, Bennett made his pitch, and then Pickering asked me to give the numbers I had. Statistics is a funny business. It has its own jargon, and I'm afraid I used a bit of it, which Bennett complained about. Froehlich interrupted, giving a very patronizing little high-school lecture about mathematics to Bennett, who got more and more pissed off as it went on. Pickering sank down into his big leather chair, wishing, I guess, that he could separate himself from Froehlich.

At this point, Eberhardt Rechtin [BS '46, PhD '50] entered the room. He was in charge of the radio and tracking system and was never one to hide his light under a bushel. (He later became head of the Defense Advanced Research Projects Agency and then head of the Aerospace Corporation.) Eb listened to about 15 or 20 seconds of the conversation and broke in, saying, "Admiral Bennett, it's perfectly clear you're just trying to throw sand in the air, you're trying to delay and postpone a project which is of vital interest to the country. It seems to me, Admiral, that you are doing something that's quite un-American." Quite a thing to say in an era of McCarthyism! Pickering put his hands over his eyes and sank even deeper into his chair. Admiral Clark rose, straightened his double-breasted Navy uniform and said, "Gentlemen, I don't think anything further can be accomplished with this conversation." He then walked to the door and held it open for everybody else to depart, and I heard him say, sort of sotto voce as Eb walked out, "You'll go far, young man."

So we were given the go-ahead to launch. There was quite a discussion as to what to name the first satellite. Our feeling came from cards, which was (and probably is) one of JPL's enduring hobbies. John Small [BS '41, MS '46, Eng '47], head of our upper-stage development group, would often wisecrack, "The winners laugh and joke, while the losers yell 'Deal!'" So we thought, having lost to the USSR the opportunity to launch first, we should call it Deal. General Madeiras, who was in charge of the program, liked Highball, and the Secretary of the Army was keen on Topkick. In the event, Eisenhower chose Explorer.

But at JPL, the preoccupation with cards stuck. Today, for example, the main tracking controller in the operations building is called "Ace" and his deputy is known as "Deuce." And a few months before that Pentagon meeting, in the blockhouse at the Cape counting down an RTV launch, there came a period of dead silence as we waited for the telemetry group to give us the go-ahead. Then out of the back room came this raucous voice, "Down for three, you bastards!"

By late January 1958, we were ready to launch Explorer 1. The Army had a Quonset hut several miles from the launchpad, and I occupied one corner of it with my crew. Our job was to do a fast analysis of all the tracking data and predict as early as possible whether the launch had been a success. We had a tracking station at the Cape, but we also needed measurements downrange. The next station was on the island of Antigua in the eastern Caribbean. Then British bases in Nigeria and Singapore, then Earthquake Valley outside of San Diego. There was nothing more between the West Coast and the Cape.

The Antigua tracking station was Navy-operated. We were allowed to put our receiver on it, although we had to use their antennas, and they never gave us a chance to test the setup. A short while before launch, they threw a switch to send the antenna output to our receiver. The switch was so badly corroded that it didn't give a signal, but we didn't know this at the time—the Jupiter had lifted off and the satellite should be visible, so why wasn't a signal being picked up? It was one hell of a problem and a little too late to start wondering what had gone wrong.

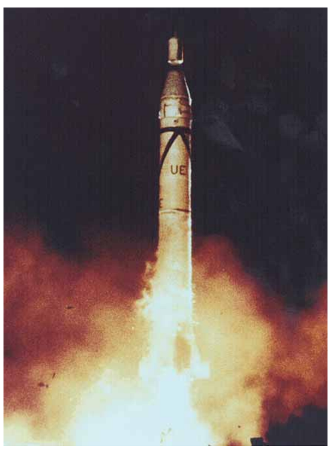
Not only were we losing valuable data, the pressure was on. Froehlich and Madeiras were having kittens across the hall from my crew, and up at the National Academy of Sciences, a press conference was due where Pickering, von Braun, and James Van Allen (who had built the instrument aboard the satellite) were waiting to announce that Explorer 1 had reached orbit.

We could, at least, get two important numbers from the Cape. First was the rocket's speed in the direction radially away from our receiving station, given by the Doppler shift of the radio signal. Second was the exact time at which the signal cut off as the satellite went over the horizon. We had hoped to get a similar pair of numbers from Antigua, as there was no way of getting real-time data from either Nigeria or Singapore. (Strange as it may seem to posterity, they didn't have phone or telegraph links with us.) With either of Antigua's numbers, we could have done a pretty good job at calculating the orbit. With both, we would have been quite exact. Without them I had to fall back on calculating probabilities.

Given the limited data, I estimated that we had a 95 percent chance of being in orbit. A satellite in a close, circular orbit, say a couple of hundred miles up, will take about an hour and a half to go around the earth. So it would take at least that long before we could get confirmation from Earthquake Valley, where we did have phone contact. I knew perfectly well that the general wanted information before then.

Of course, there were big computers at the Cape, and they were also using radar and radio data to track us. I learned later from the range safety officer that his computers—never very reliable—had indicated that the rocket was going to come down in Tampa. Since we had all watched it lift off as a brilliant point of light in the night sky moving steadily east, he knew that wasn't the case. He had graciously refused to blow it up, as he would have done if it really was headed toward a Florida city.

After about half an hour, I went in to see Madeiras, and I started giving him the probabilities. He said—and I quote—"Don't give me any of this probability crap, Hibbs. Is the thing up there or not?" (Madeiras later became an Episcopalian minister. Maybe he liked their probabilities of reaching the heavens better.) Well, the most likely solution was that it was up, with a very high apogee and a satisfactory perigee, so it would probably stay up. My best guess from the little data we had on the upper atmosphere was that it would stay up for about 15 years. So I told Madeiras that we were



Explorer I lifted off at 10:48 p.m. on January 31, 1958, on a Jupiter-C rocket, von Braun's modification of the Redstone ballistic missile that was itself a direct descendant of the German V-2. The Army Ballistic Missile Agency and JPL finished modifying the rocket and built and launched Explorer in just 84 days.

PICTURE CREDITS:
38, 39 – NASA

From left: Pickering, Van Allen, and von Braun hold a model of Explorer I and the final stage of its rocket aloft at the press conference. Explorer's payload included a cosmic-ray counter, which discovered the lower Van Allen belt—a zone of charged particles trapped by the earth's magnetic field.

in orbit. Explorer 1 stayed up for a little more than 12 years, so it wasn't too bad a calculation under the circumstances.

After my report, Madeiras and Froehlich took off in an Air Force car for an auditorium at Patrick Air Force Base, where a press conference had already been called. The reporters were sitting around anxiously waiting for somebody to show up and tell them what had happened. I was in one of the last cars to go. While I was waiting, I was overcome by a strange mixture of emotions. I was staring up into the sky, quietly crying, for it was a complete letdown: several years of intense work were over, and, apparently, successfully. My feelings were simply, "We did it!"

At the auditorium, I asked a guy in my group, Chuck Lundquist, on loan from Huntsville, to get in touch with Earthquake Valley and keep the line open. (I was up on stage behind Madeiras, who was going to speak to the press.) Chuck was to come out of the phone booth and signal me as soon as he heard anything. Until then, he was to come out every five minutes and signal "not yet."

We knew it would be a while, because the high apogee meant the orbit would be longer than 90 minutes. In fact, it was more than two hours. Everybody was getting pretty nervous, even me, although I should have known better—I was the one who had predicted when it should arrive. Madeiras, bless him, trusted me implicitly, and fended questions from the press by saying repeatedly, "Don't worry, we'll hear from it."

Meanwhile, up in Washington, Pickering, von Braun, and Van Allen were on stage and fully aware that 90 minutes had gone by with no sign of the satellite. After 90 minutes, someone walked over to Pickering and said, "Well, better luck next time, Bill, I guess you didn't quite make it, chuckle, chuckle, chuckle." But Pickering sat quietly and said, "I'll wait till my boys tell me that." Of course, I had already told him by phone that it was up, but I think he wanted to be a little more certain.

It was almost two hours after launch that Chuck gave me the sign—thumb and forefinger together in a circle—that all was well. I walked up to whisper the same in Madeiras's ear, and he announced the result to the press and the waiting world. □

Anne Marie Buck
1939 – 2003

Anne Marie Buck, university librarian since 1995, died of cancer April 2 at the age of 63. She presided over the Caltech library system during a revolution in information technology and scholarly communication and led it into the new age, which she embraced with enthusiasm.

A memorial service was held at the Athenaeum April 11 for colleagues, family, and friends to "share our grief, to mourn our loss, and, most of all, to celebrate Anne's life," as President David Baltimore said in his opening remarks.

Buck was born in 1939 in Birmingham, Alabama, and graduated with a BA in geology from Wellesley College in 1961. She began her library career in 1974 as director of the Dunbar Public Library in West Virginia after her two children were in school, and returned to graduate school to earn her master of library science degree from the University of Kentucky in 1977, when she was 38. For a number of years thereafter, she held several key positions at Bell Laboratories. After the breakup of AT&T, she established and directed the Bellcore Library Network and served for two years as director of Bellcore's human resource planning. She taught library management at

Anne Buck loved to travel, and photos of "Bucky's" journeys to far-flung places were shown at the memorial service. Here she is at Olduvai Gorge in Tanzania (right) and Angkor Wat, Cambodia (left).

Rutgers University and the University of Wisconsin, and, from 1991 until coming to Caltech, she was university librarian at the New Jersey Institute of Technology. Buck served as vice president of the Engineering Information Foundation and initiated that group's Women in Engineering Program, dedicated to increasing the number of women in that field.

At the memorial service, Baltimore praised her "organizational skills, her love for words and books," but he also noted her feistiness, her "quirky humor," and her "characteristic good cheer," indelible aspects of her personality that were subsequently echoed by other speakers.

"Anne was gutsy," said Kimberly Douglas, director of Caltech's Sherman Fairchild Library of Engineering and Applied Science. "She spoke her mind even when perhaps it wasn't always in her best interest. And she lived and worked with a gusto, a vitality and enthusiasm that manifested itself in all aspects of her life."

Douglas first met Buck when the latter was interviewing for the Caltech position. The design of the new Fairchild Library was close to completion. "In the library we sensed we were entering upon a new era, though we were not exactly sure what that would entail. We knew we needed someone different, a strong person with a fresh view, a champion for the library to follow a new path."

For someone of a generation introduced to computers "at a mature age, Anne stood out in her insight into the utility and potential of the information revolution we were undergoing," said Douglas, who described Buck's instrumental role in organizing a 1997 conference on scholarly communication, which explored a greater role for electronic publishing. But "the greatest gift that Anne gave the library was, without a doubt, her enthusiastic support of the library staff and the role and service that libraries provide within a research institution," Douglas continued. "Her unwavering and vigorous support over the last years now leaves the library staff fully confident and equipped to successfully meet the coming challenges Caltech faces. We have much to thank her for."

Richard Flagan, the McCollum Professor of Chemical Engineering, was chair of the faculty library committee when Buck arrived at Caltech at a time of skyrocketing journal prices. The two of them faced the task of cutting 30 to 40 percent of the journal subscriptions without alienating the faculty. Buck managed to keep the faculty involved in the process, said Flagan, and made sure that essential needs were still met.

"Anne did not limit her efforts to dealing with the immediate problems, however," said Flagan, "but rather embraced a vision in which the developing Internet becomes a medium through which academic researchers could reclaim control of scholarly communication." Buck, Flagan, and Provost Steve Koonin organized the 1997 conference to bring together librarians, professors, journal publishers from academic societies, and provosts ("the people who pay the bills") to discuss how the Internet could be used "to serve the needs of the research community in communicating the results of their research." Flagan credited Buck with designing the program and attracting participants who could offer some radical proposals for the future of the scholarly journal.

Buck and Flagan subsequently published their own proposal for publishing, indexing, and archiving electronic journals—"Scholars Forum: A New Model for Scholarly Communication." They posted it on the Internet. Flagan claims it's his most cited paper.

In the future world of electronic publishing, Buck saw libraries continuing in their traditional role of archiving. But she saw more than that. Anne's vision, said Flagan, was that libraries "can continue their role of preservation, not through simply storing the material, which has been possible with paper, but by taking a much more active role in translating it from medium to medium as technology changes require."

"She transformed the libraries at Caltech from mere repositories for the works published elsewhere to a leader in the move toward active preservation and dissemination of the knowledge discovered and created on this campus."

Joan Wilson, president of the Friends of the Caltech Libraries (FOCAL), described Buck as a "superdedicated professional with ideas and imagination. We are going to miss her spunky personality and thoughtful take on where the world of libraries should be in the 21st century."

Buck's son, Stephen, shared

a “top-10 list” of what made his mother one of a kind, including her rigorous planning, her love of traveling “by methods we normally only want to read about,” her passion for collecting obscure items and rocks, and (number one) her fastidiously indexed filing cabinet, from which she could pull information on almost any topic. “For all those who needed information before the Internet and Google, there was Anne Buck.” Besides her son, Buck is survived by a daughter, Susan Buck Rentko, and two grandchildren, Elizabeth and Christopher Rentko.

Other friends, family members, and colleagues—from her grad school days, from her job at Bell Labs, from organizations she belonged to, from her travels—offered brief remarks on their friendships with Buck and her meaning to their lives. Several commented on the grace and courage with which she faced her final illness.

“Anne was a tough cookie,” said Eric Van de Velde, director of library information technology at Caltech. “I had my share of confrontations with her and she relished it. But she never faulted me for disagreeing with her and for fighting for my point of view. Her toughness continued to her last days. There was not a hint of self-pity, and pity was the last thing she wanted from us. So therefore I don’t offer words of pity now. I only offer a heartfelt congratulations to Anne on wrapping up an impressive life.” □ *—JD*

Gilbert D. McCann 1912 – 2003

Gilbert Donald McCann, professor of applied science, emeritus, died in Solvang on April 9, aged 91. He was the driving force behind computing at Caltech for 25 years (and a professor for 34), starting in 1946 with an analog computer that he invented, continuing through the time when new materials, miniaturization, and software transformed digital computing and made the analog obsolete, to the time when every department was using computers small enough for desktops.

Born in Glendale in 1912, McCann studied electrical engineering at Caltech, gaining a BS in 1934, an MS in 1935, and a PhD in 1939, before joining Westinghouse in Pittsburgh to study natural lightning phenomena. A photograph of the young McCann sitting calmly in a car being struck by a three-million-volt bolt of electricity went around the world, but he had not always been so lucky when experimenting with electricity: as a graduate student, a two-million-volt stroke from a surge generator he had built paralyzed all his outer nerves and muscles for 24 hours and left a large cataract in one eye. An unknown person had switched off the spark-gap ground, and the lightning bolt jumped straight to his metal-rimmed glasses.

Research at Westinghouse was diverted to supporting the military during World War II, and McCann set to work to devise a way of doing complex engineering calculations using electrical circuits to simulate mechanical forces—the basis of his analog computer. The machine he invented could do calculations that would previously have taken years. It enabled him to design a rapid feedback-control system for improving the tracking accuracy of antiaircraft guns. Rushed to the gun batteries defending England’s east coast just a month before the Germans launched their massive V-1 bomber attack, the system enabled most of the V-1s to be shot down as they crossed the coastline.

Persuaded to return to Caltech after the war (not least by his wife, Betty, who missed Southern California), he started as an associate professor of electrical engineering in 1946, rising to professor a year later. He immediately set up an analysis lab to make a larger, improved version of his analog computer. Westinghouse was already at work on one when he left, and he negotiated a deal whereby they would make two of everything and ship the second set to Caltech for a very good price. Assembled in the Norman Bridge Laboratory of Physics with the aid of Charles Wilts (BS ’40) and Bart Locanthi (BS ’47), the huge calculator weighed in at 33,000 pounds. Though without a catchy name like its Westinghouse twin, the Anacom, Caltech’s direct analogy electrical analog computer was soon providing an invaluable service for JPL, the military, and the entire Southern California aerospace industry, all of whom lined up to have their

McCann sits at the console of his direct analogy electrical analog computer, a behemoth that took up all sides of this large room in 1958. The results of engineering calculations were read from the oscilloscope above the console.

engineering problems solved, particularly those related to missile guidance systems and jet airplane design. At one stage, McCann recalled, every aircraft company in America and Europe was a customer, and in 1950, *Engineering & Science* reported that the lab was "too busy to take on all the problems which have been submitted." "It was a world-class computing instrument at the time," said Carver Mead. "It could do things nobody else could do anywhere." But by the early 1950s, the fact that the analysis laboratory was becoming a computer bureau to service the needs of industry got to be too much for Caltech, particularly Clark Millikan, director of the Guggenheim Aeronautical Laboratory. He suggested spinning off a commercial company, and Computer Engineering Associates was formed. McCann was the largest shareholder, but could not run the company because he would have had to resign his faculty position.

An engineer at heart, he initially saw digital computers as a sideline "for the physical chemists." The analog computer was faster, but its accuracy was limited to 1 or 2 percent, more than enough for engineers but not good enough for mathematicians, so in 1949 he recruited Stanley Frankel to head a small but highly innovative digital-computing unit, an excellent choice because, by the early 1950s, Caltech was one of the leading centers in both analog and digital computing. McCann's graduate students were now focusing more and more on miniaturization and innovative materials for digital computers, and there was also the Computer Center on the first floor of the Spalding Laboratory of Engineering to run. When IBM donated a massive 7090 in 1961, McCann led a successful fund-raising campaign for a new building to house it and, when the Willis H. Booth Center for Computing (now Powell-Booth) was dedicated in 1963, he became director for the first seven years. In 1966, he was made professor of applied science, the position he held until his retirement in 1980, after which he was made emeritus.

In the late '40s, a collaboration with Werner Reichardt, his German equivalent during the war and later director of the Max Planck Institute for Biological Cybernetics in Tübingen, sparked his interest in applying computers to analyzing how brains work, especially how they perceive and process vision, and he pursued this research throughout his time at Caltech. Fred Thompson (professor of applied philosophy and computer science, emeritus) remembers McCann using beeswax to mount houseflies on a stand in the center of a large, six-foot sphere with flashing images (dubbed the planetarium). Gold fibers inserted into their brains captured data from individual neurons as they responded to visual signals, which were fed into the computer. A notice outside the lab door said "Do not commit insecticide." Over the years McCann worked closely with Caltech biologists to study other animal brains, including those of honeybees, fruit flies, earthworms, fish, and humans.

As to what happened to the analog computer, McCann recounts in his memoirs that in the 1960s a small company in Santa Paula contacted him asking for one, long after Computer Engineering Associates had been sold off and the Caltech computer dismantled and stored in a warehouse. "I bought enough parts for their computer from Caltech for a song, and Bart Locanthi, my son Norman and I built it in Bart's garage," he recalled, adding that the deal made him enough money to travel to Germany to buy a much-desired 1954 Mercedes 300 convertible to add to his classic-car collection.

He received the Eta Kappa Nu Award for Outstanding Engineer in 1942 and the Glen A. Fry Lecture Award of the American Optometric Foundation in 1979, and he was a fellow of the Institute of Electrical and Electronics Engineers, as well as a Caltech Associate. A keen gardener and breeder of Arabian horses, he and Betty moved in the mid '80s to their horse ranch near Solvang. Betty predeceased him in April 2002, but he is survived by his son, Norman; his daughter, Janice; and a brother, Louis. The family requests that donations in his memory be sent to Caltech at the California Institute of Technology, Development Office 105-40, Pasadena, CA 91125. ☐ —*BE*

Lange Named California Scientist of the Year

Andrew Lange, the Goldberger Professor of Physics, has been named California Scientist of the Year for 2003 by the California Science Center, the 14th Caltech faculty member to win that honor. He shares the award with Saul Perlmutter, senior scientist and group leader at the Lawrence Berkeley National Laboratory in Berkeley.

Using two very different techniques, Lange and Perlmutter's experimental efforts have confirmed a remarkable theory of how the universe expanded and evolved after the Big Bang. The selection panel of the California Science Center concluded that Lange and Perlmutter's discoveries complement each other so well in revealing the nature of the universe that both scientists should be recognized this year.

Lange studies fluctuations in the cosmic microwave background (CMB) radiation, a relic of the primeval "fireball" that filled the early universe (see *E&S,* No. 3, 2000). These signals, which are visible today at microwave frequencies, provide a clear "snapshot" of the embryonic universe at an epoch long before the first stars or galaxies had formed. In general, this radiation reaches the earth uniformly from all directions in the sky. However, at the level of 0.003 percent there is an intricate pattern of fluctuations in the CMB. Using novel detectors developed at the Jet Propulsion Laboratory and flown on a balloon-borne telescope high above Antarctica, Lange's group was able to make the first resolved images of these very faint patterns. The images demonstrate that the radiation fluctuates on an angular scale of one degree, which is exactly what scientists expected from a mathematically flat universe, which, according to Einstein's general theory of relativity, places constraints on the amount of mass and energy in the universe.

Perlmutter's work indicates that the source of astronomical energy giving rise to a flat universe comes from a type of negative gravitational pressure or dark energy permeating the universe. □

Three elected to AAAS

The American Academy of Arts and Sciences has elected three Caltech faculty members as academy fellows. They are Fred C. Anson, the Gilloon Professor of Chemistry, Emeritus; Joseph L. Kirschvink, professor of geobiology; and Colin F. Camerer, the Axline Professor of Business Economics.

Anson has carried out pioneering work on the electrochemistry of polymers, on the catalysis of electrode reactions, and on electrochemical reactions that involve ultrathin coating of molecules on electrode surfaces.

Kirschvink, who has been honored by students for his excellence in teaching, studies how biological evolution has influenced, and has been influenced by, major events on the surface of the earth. His most significant contributions include the "snowball" earth theory—the theory that the entire planet may have actually frozen over several times in its history, possibly stimulating evolution. Another original concept concerns the Cambrian evolutionary explosion that he believes may have been precipitated in part by the earth's rotational axis having moved to the equator in a geologically short interval of time.

Camerer's research in experimental and behavioral economics integrates psychology with economics to explore the impact on decision sciences and game theory. His research uses economics experiments and field studies to understand how people behave when making decisions. Such research is helpful in predicting economic trends and in understanding social policy. Poverty, war, cross-cultural interactions—most social issues are affected by decision psychology.

The total number of Caltech faculty named to the academy is now 82. □

New Faculty Officers

David Goodwin, professor of mechanical engineering and applied physics, has been elected new chair of the faculty; Henry Lester, the Bren Professor of Biology, will serve as vice chair; and David Wales, professor of mathematics, will continue as secretary of the faculty. They will serve two-year terms, beginning July 1.

The faculty files—into Commencement 2003.

Other Honors and Awards

Six Caltech professors received Alfred P. Sloan Research Fellowships for 2003, which provide grants of $40,000 over a two-year period to young researchers to allow them the freedom to establish their own independent research projects at a pivotal stage in their careers. They are Paul David Asimow, assistant professor of geology and geochemistry; Linda C. Hsieh-Wilson, Jonas C. Peters, and Brian M. Stoltz, assistant professors of chemistry; Danny Calegari, associate professor of mathematics; and Athanassios G. Siapas, assistant professor of computation and neural systems. Stolz also received a $180,000 grant over three years from Johnson & Johnson's Focused Giving Program to continue his research on developing anti-leukemic drugs derived from the yew tree.

The 2003 ASCIT Teaching Awards went to Warren Brown, associate professor of history; Ada Chan, Bateman Research Instructor in Mathematics; John Eiler, assistant professor of geochemistry; James Eisenstein, professor of physics; and Ritsuko Hirai Toner, lecturer in Japanese.

Donald Helmberger, Smits Family Professor of Geophysics and Planetary Sciences and director of the Seismological Laboratory, has been awarded the 2002 Medal of the Seismological Society of America. The award is "given to persons for outstanding contributions in seismology and earthquake engineering who are distinguished for their attainments in seismology or related sciences, or for their service to the profession or the Society."

Michael Hoffmann, the Irvine Professor of Environmental Science and dean of graduate studies, gave the third annual Harold S. Johnston Lecture at UC Berkeley on March 18; the title of his lecture was "Photochemistry in Ice: Nitric Acid Photolysis and the Production of NO_2 and NO."

Alexander Kechris, professor of mathematics, is a corecipient of the 2003 Carol Karp Prize, which he shares with Greg Hjorth, a mathematics professor at UCLA. Awarded by the Association for Symbolic Logic, the prize is given every five years for a "connected body of research, most of which has been completed in the time since the previous prize was awarded," and this year recognizes the recipients' work on Borel equivalence relations. The prize consists of a cash award.

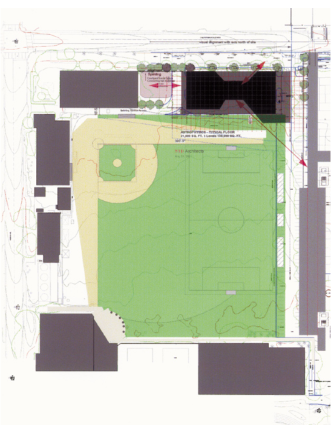
Joseph Kirschvink, professor of geobiology, has had an asteroid named after him. The asteroid (27711) Kirschvink was discovered at Palomar Observatory in 1988 by the late Gene Shoemaker and his wife Carolyn, who named it for Kirschvink.

Anneila Sargent, professor of astronomy and director of both the Owens Valley Radio Observatory and the Interferometry Science Center, has been named to the United Kingdom's Particle Physics and Astronomy Research Council (PPARC). Sargent, who has been president of the American Astronomical Society and chair of NASA's Space Science Advisory Committee, is expected to provide an international perspective to PPARC. Her appointment is for four years. She has also been selected for the 2003 George Darwin Lectureship of the Royal Astronomical Society.

The Caltech Graduate Student Council gave its Mentoring Award to Re'em Sari, associate professor of astrophysics and planetary science, and its Teaching Award to Mark Wise, the McCone Professor of High Energy Physics. The GSC Teaching Assistant Awards went to grad students Justin Bois in chemical engineering and Kumar Manoj Bobba in aeronautics. □

A tentative concept study shows the Cahill Center for Astronomy and Astrophysics as seen from the athletic field.

New Center for Astronomy, Astrophysics



The new building will face California Boulevard next to the Keith Spalding building.

Astronomy and astrophysics are enjoying a period of unprecedented progress and growth. Caltech's scientists are shedding new light on how stars, planetary systems, and the universe were formed. At the same time, they are developing the technologies that will usher in the discoveries of tomorrow.

Today, Caltech's observing facilities—which span the entire electromagnetic spectrum—are unmatched by almost any other institution worldwide. The physical space for our astronomy and astrophysics teaching and research programs, however, is at maximum capacity and spread among four different buildings.

The solution to this problem has taken shape in a proposed 100,000-square-foot facility that will provide a collective home for Caltech's varied programs in this area.

"Pulling together the division's many activities in astronomy and astrophysics to achieve optimal synergy has been our goal for some time," says Tom Tombrello, chair of the Division of Physics, Mathematics and Astronomy. "The proposed building is an essential ingredient in this progression and, naturally, a top priority for us."

The new facility will be named the Cahill Center for Astronomy and Astrophysics in recognition of a $20-million lead commitment from Caltech friend Charles H. Cahill. Such support will enable the Institute to create an environment for productive interaction among observers, instrument builders, and theorists, enabling our scientists and engineers to continue to contribute new breakthroughs far into the future concerning the birth, structure, and fate of the universe.

"Mr. Cahill's generosity reinforces this project's role in Caltech's future," Tombrello adds. The much anticipated facility is a significant component of the Institute's $1.4-billion "There's only one. Caltech" campaign.

The Cahill Center will be located adjacent to the Keith Spalding building on the south side of California Boulevard. Initial plans for the new facility include a lecture hall, classrooms, spaces for laboratories and remote observing, a library, conference rooms, and offices. In addition, laboratories will be grouped by discipline to encourage interaction and synergy among researchers with similar and overlapping scientific interests.

To replace parking lost as a result of the new building, a parking structure will be constructed underneath the Institute's athletic field—this phase of the comprehensive building plan could begin as early as October 2003 and be complete by September 2004. During that time, the project's final architectural and engineering plans will be initiated, with actual construction on the Cahill Center to follow some time after the completion of the parking structure. ☐ —*Vannessa Dodson*

For more information on the campaign, visit the web site at http://one.caltech.edu.

Or contact:
California Institute of Technology
Development and Alumni Relations
Mail Code 5-32
Pasadena 91125

Phone: 1-877-CALTECH
or Principal and Major Gifts:
(626) 395-6947

there's only one.caltech
THE CAMPAIGN

Engineering & Science

California Institute of Technology
Pasadena, California 91125