California Institute of Technology

Engineering and Science

Volume LXII, Numbers 1/2, 1999

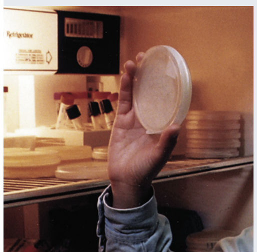
IN THIS ISSUE

Forget Yogi Bear and Boo-Boo—there's more life in this picture of the Norris Geyser Basin in Yellowstone National Park than meets the eye. Bacteria thrive in the scalding throats of geysers, and in other environments even more exotic. To see how these bugs are informing NASA's strategy for looking for life beyond Earth, read the story on page 30. To find out how their offspring may sire a nonpolluting chemicals industry, turn to page 40. Photo courtesy of Diversa Corporation.

California Institute of Technology

ENGINEERING AND SCIENCE

Volume LXII, Number 1/2, 1999



On the cover: Molten magma leaks out from Earth's insides in volcanoes like Hawaii's Kilauea, whose Kupaianaha lava lake splashes here. Why are volcanoes where they are? And why aren't they everywhere? Don Anderson, in an article beginning on page 10, answers these questions and describes his theory of a compressed lithosphere keeping the lid on a layered mantle. Photo by Dorian Weisel.

http://www.volcanophoto.com

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: 2, 28, 45, 47 – Bob Paz; 3 – John Allman; 4, 5, 22, 26, 32, 33, 39 – NASA; 6 – Art Chirino; 8, 10, 17 – Charlie White; 20 – Luis Gonçalves, Dean Schonfeld; 22 – Luis Gonçalves; 24 – Mario Munich, Dean Schonfeld; 25 - Mike Burl, Markus Weber; 27, 28, 29 – Jean-Yves Bouguet; 30 – E. Imre Friedman; 34 – Lynn Margulis; 37 – Henry Sun, John Baross; 38 – Raul Cano, David Gilichinsky; 40 – Jeff Moore; 40, 50 – Robert Todd; 42-44, 45, 47, 50 – Frances Arnold; 44 – Makoto Yagasaki; 46 – Doug Smith; 48 – Anne Gershenson; 49 – Anne Fu

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

The April 2 dedication of the Powell-Booth Laboratory for Computational Sciences showcased, among other things, the Immersadesk large-screen 3-D projector. Virtual passengers included (from left) President Baltimore, the Powell Foundation's Larry Cox, and Professor of Civil Engineering and Applied Mechanics Paul Jennings. The lab also contains a Hewlett-Packard Exemplar, the world's largest cache-coherent shared-memory computer.

The Whittier Foundation Expresses Itself at Caltech

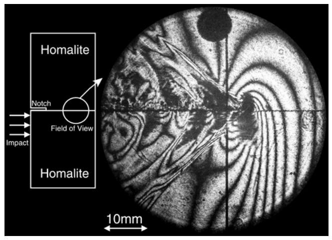
Caltech has received a $1,444,000 grant from the L. K. Whittier Foundation to found the L. K. Whittier Gene Expression Center. Led by Professor of Biology Barbara Wold (PhD '78), the center will use Caltech's unique resources to begin large-scale human gene expression analysis. Mel Simon, chair of the biology division and the Biaggini Professor of Biological Sciences, has produced probes for 40,000 known human genes, and for many of the genes characterized in the mouse. By combining this information with what scientists have already learned from the Human Genome Project, the center is expected to produce wide-ranging discoveries in both the medical and biological sciences. "We hope to make the center a useful tool for all of the biologists on campus, and ultimately for scientists around the world, through our accumulated database of gene-expression information," says Stephen Quake, associate professor of applied physics and another collaborating scientist at the center. "Gene arrays provide more data than any one person can analyze, and the aggregate sum of the data provides a powerful resource to answer a number of questions about gene function." □—*SMcH*

Self-Awareness Neurons

Clusters of large neurons found exclusively in the brains of humans and other primates closely related to humans may provide these species with enhanced capacities for solving hard problems, as well as for self-control and self-awareness. In the April 27 issue of the *Proceedings of the National Academy of Science*, neurobiologists Patrick Hof from Mount Sinai Medical Center and Caltech's John Allman, Hixon Professor of Psychobiology and professor of biology, and their colleagues have found an unusual type of neuron that is likely to be a recent evolutionary acquisition. The neurons in question are spindle-shaped cells that are almost large enough to be seen with the naked eye and are located in the frontal lobe near the corpus callosum, which connects the two halves of the brain.

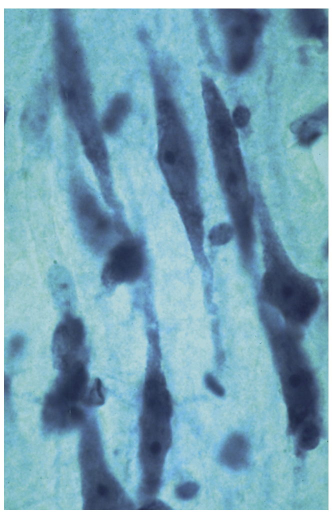
Allman, Hof, and their team studied 28 different species of primates and found the spindle neurons only in humans and very closely related apes. The concentration of spindle neurons was greatest in humans, somewhat less in chimpanzees, still less in gorillas, and rare in orangutans. According to Allman, "This declining concentration matches the degree of relatedness of these apes to humans." There were no spindle cells in gibbons, which are small apes, or in any of the other 22 species of monkey or prosimian primates they examined. The spindle cells were also absent in 20 nonprimate species examined, including various marsupials, bats, carnivores, and whales.

The cells are found in an area of the brain already linked to psychiatric diseases. Says Allman, "In brain-imaging studies of depressed patients, there is less neuronal

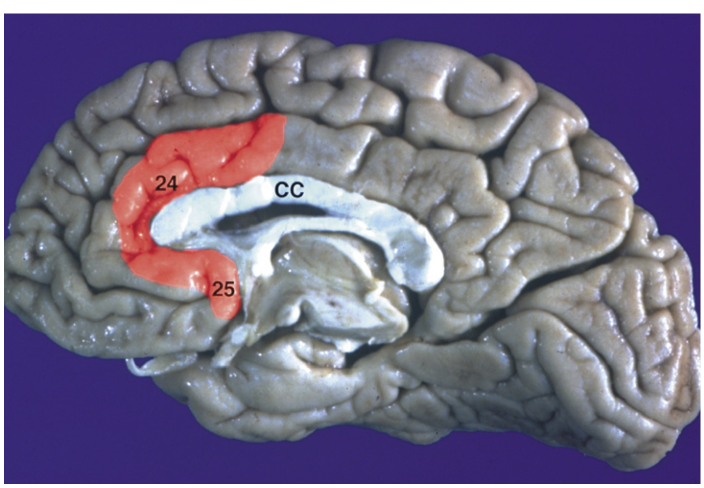


When a brittle material breaks, the cracks spread like lightning, as anyone who has inadvertently subjected a favorite vase to "floor stress" knows. But how fast is fast? In the May 21 issue of *Science*, Professor of Aeronautics and Applied Mechanics Ares Rosakis and grad students Omprakash Samudrala and Demirkan Coker used an ultrafast camera running at two million frames per second to show that for cracks resulting from shear stresses traveling along weak planes, the speed of the crack can exceed the speed of sound in the material, creating angled shock waves (the > shape) that closely resemble photographs of a supersonic bullet breaking the sound barrier. This crack is moving at about 2,200 meters per second, or 5,000 miles per hour. Rosakis hopes that studying how such cracks get going will help seismologists understand how earthquakes begin along shear faults, such as California's notorious San Andreas.

activity in the region and the volume of the area is smaller. The activity of the area is increased in manic and obsessive-compulsive patients." The area's activity has been shown to increase with the difficulty of the cognitive task being performed, suggesting that the area enhances the capacity to do hard thinking. Activity also increased when a subject withheld a response or focused its attention, suggesting the area is involved in self-control. Furthermore, the spindle neurons themselves are especially vulnerable to degeneration in Alzheimer's disease, which is characterized by diminished self-awareness. From this Allman suggests, "Part of the neuronal susceptibility that occurs in the brain in the course of age-related dementing illnesses may have appeared only recently during primate evolution." □—*RT,*



Left: The spindle cells.
Below: The cells live in the anterior cingulate cortex, shown in red in this view of the bisected human brain.



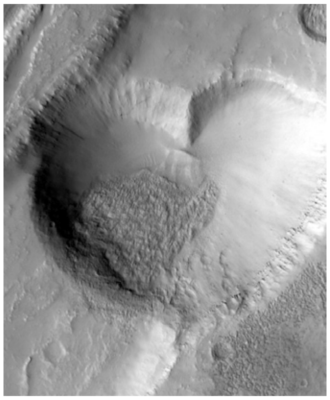
The CENIC Route to Mexico

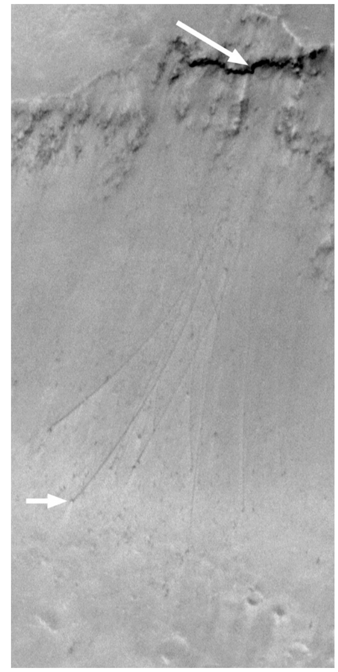
Plans for a new high-speed Internet2 linkage between California and Mexico were unveiled in San Diego on May 19, when Governor Gray Davis and President Ernesto Zedillo endorsed a joint memorandum of understanding. The memorandum establishes an agreement for the linkage between California's Corporation for Education Network Initiatives in California (CENIC), of which Caltech is a member, and Mexico's Corporacion Universitaria para el Desarrollo de Internet (CUDI). "Linking together Mexico's and California's advanced networks will enable our universities to share powerful instruments and supercomputers, enrich learning through real-time interactions, share medical research and diagnostic capabilities, and reach into each others' libraries," said M. Stuart Lynn, Chairman of the CENIC Board. "Together, we can solve important educational, social, and research problems to improve the lives of people everywhere." □

The Planetary Travel Report

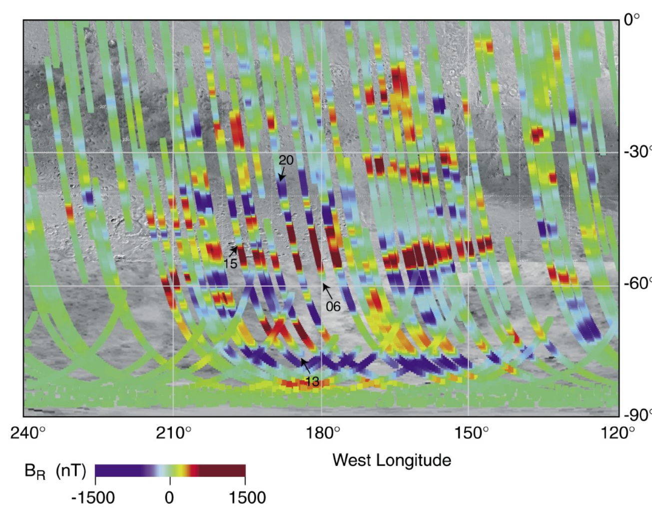
Mars is the solar system's happenin' tourist destination these days. There's the Mars Global Surveyor, which settled into its final mapping orbit on February 19, deployed its high-gain antenna on March 28, and began its somewhat deferred primary mission on April 4. The Mars Climate Orbiter and the Mars Polar Lander are well on their way, having lifted off on December 11 and January 3 respectively. The former is set to slip into orbit on September 23; the latter to land near the south pole on December 3. The lander is actually two missions in one, as it carries two microprobes collectively known as Deep Space 2 that will hit the Martian surface at some 200 meters per second (400 miles per hour) and bury themselves as much as a meter deep in search of water ice.

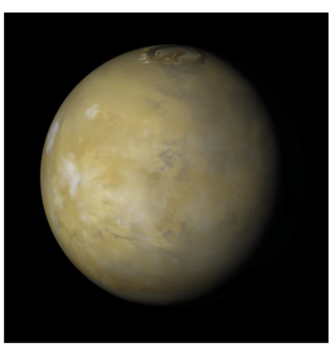
By the way, it's no longer the Red Planet—in the 575-page compendium of results from the Mars Pathfinder mission published as a special section of the April 25 issue of the *Journal of Geophysical Research*, one conclusion was that the planet is actually various shades of yellowish brown. (Our eyes don't perceive these hues well from afar and so see them as red, which has colored our thinking.) Whether "The Butterscotch Planet" will catch on with the Martian Board of Tourism remains to be seen.

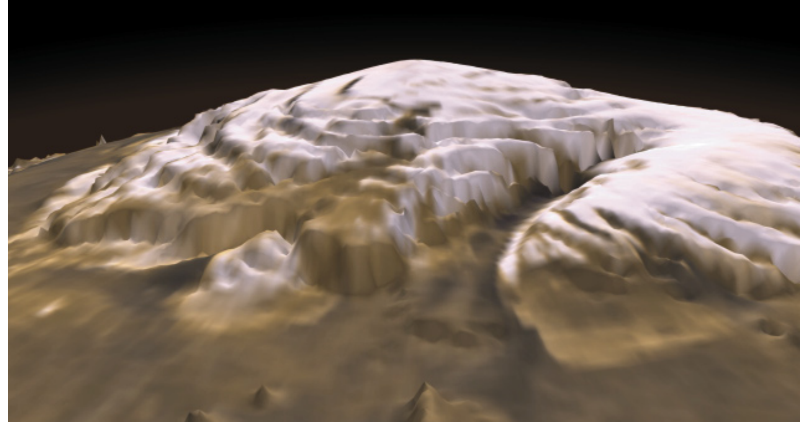




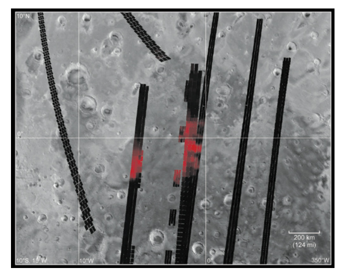
Aboard the Mars Global Surveyor, the Mars Orbiter Camera (MOC), built and operated by Michael Malin (PhD '76) and Malin Space Science Systems, continues to be a workhorse, but other instruments are cranking out data as well. Clockwise, from the top left: (1) This Martian valentine is actually a pit about a mile and a half wide, formed by the collapse of subsurface material. (2) The "Happy Face Crater," officially known as Galle, is about 134 miles across and lies on the east flank of Argyre Planitia. (3) The large arrow points to a steep cliff of dark rock from which several boulders appear to have broken off, leaving a fan of trails down the soft, dusty slope. The small arrow points to one such boulder, approximately 18 meters in diameter—bigger than a two-story house. (The MOC can actually see boulders as small as 1.5 meters, or five feet, in diameter—the size of Yogi rock at the Pathfinder landing site.) (4) Data from the Mars Orbiter Laser Altimeter provide a global relief map—see page 33 for another view. (5) Global nighttime (2:00 a.m.) surface temperatures from the first 500 mapping orbits, as measured by the Thermal Emission Spectrometer. It's winter in the southern hemisphere, and the coldest temperatures mark the polar ice cap. Along the equator the coldest areas are very fine dust; warmer regions, such as the Valles Marineris (10° S, 30–90° W), are coarse sand, gravel, and rocks. The north pole gets full sunlight, and is relatively warm. (6) The discovery of these magnetic stripes, which may be the signature of long-extinct plate tectonic processes, was a bonus from the aerobraking orbit's dipping below the ionosphere—at mapping altitude, the magnetometer would not have been able to see them. (7) Mars—the butterscotch planet.

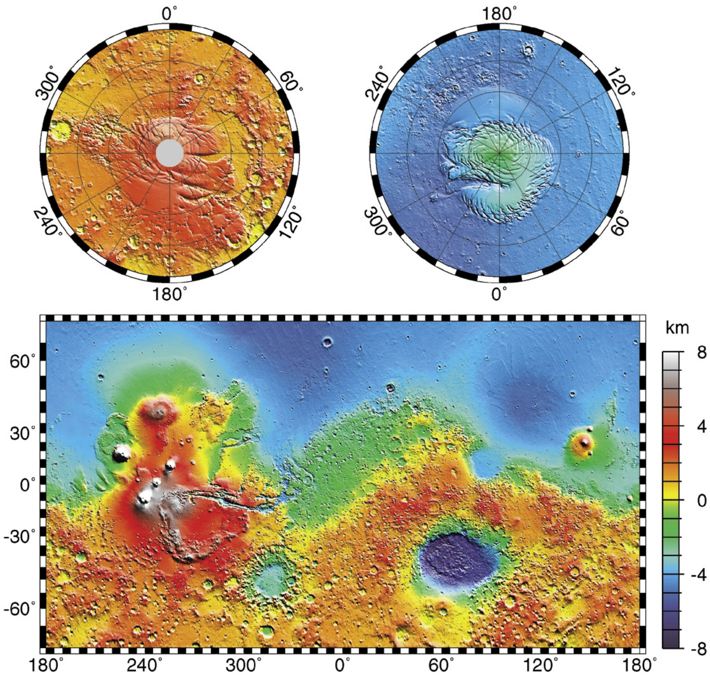


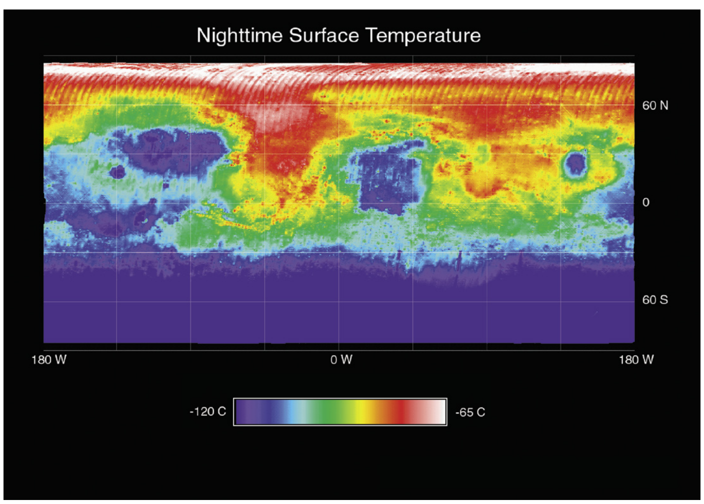




Above: The first ever 3-D picture of Mars's north pole (vertical scale exaggerated), as measured by NASA/Goddard's Mars Observer Laser Altimeter. The elevation data is accurate to 5–30 meters over a spatial resolution of one kilometer, and will allow scientists to better estimate the volume of water in the polar ice cap.
Below: The Thermal Emission Spectrometer, run by Arizona State, also maps surface mineralogy by their spectral fingerprints. Here hematite concentrations are shown in red—black pixels mean no detectable hematite was found. The data is superimposed on a Viking image.



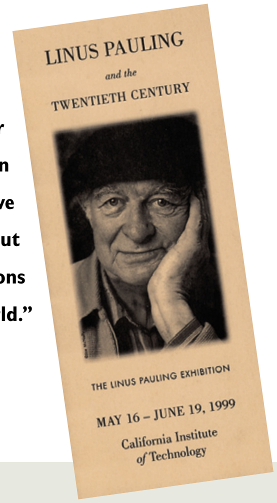




Meanwhile, beyond the asteroid belt, Galileo continues exploring the Jovian system, particularly the moon Europa. The latest news there is that Europa's nighttime temperatures show puzzling variations from place to place—patterns that don't correlate with either the surface's geology or reflectivity. (The daytime temps are as expected.) The spacecraft has also detected hydrogen peroxide, a powerful chemical perhaps best known on Earth as "blonde in a bottle," on Europa's icy surface. Hydrogen peroxide reacts with pretty much everything and so doesn't hang around long (it's not found naturally on Earth), so it appears to be forming continually as energetic particles from Jupiter's radiation belts smash into Europa and break down other molecules. On other moons, Galileo has discovered a cloud of microscopic dust grains, believed to be from meteoroid impacts, around Ganymede, and a thin atmosphere of carbon dioxide—so thin that the molecules literally drift around without colliding with one another—on Callisto. This latter finding means that all four of Jupiter's largest moons have some sort of atmosphere, no matter how tenuous.

And from the "If it's Tuesday, it Must be Belgium" department, Cassini hit another milestone on its roundabout, gravity-assisted trajectory to Saturn by buzzing Venus for the second time on June 24th. Next stop is Earth on August 18.

During the month that the exhibition *Linus Pauling and the Twentieth Century* occupied the Winnett Center, a total of 16,000 people visited it, 3,300 of them students from local schools. Sponsored by the Pauling family with Oregon State University, Caltech, and Soka Gakkai International, the exhibition, subtitled "A Quest for Humanity," celebrated Pauling's life—his work in peace as well as in science—through photos, historical artifacts, papers, and interactive workstations. Part of its mission was "to teach today's youth about the role of scientists in creating conditions for a secure and peaceful world."



Watson Lectures Set

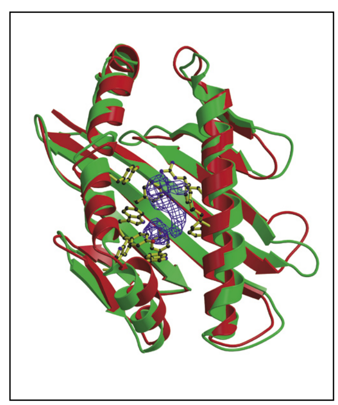
Next fall's Watson lecture lineup has been announced. Opening the season on October 6 will be "Grocery Bags to Baseball Bats: Polymers and Us" by Robert Grubbs, the Atkins Professor of Chemistry. Next comes "Stem Cells to the Rescue" by David Anderson, professor of biology and investigator at the Howard Hughes Medical Institute, on October 20. On November 3, Professor of Finance Peter Bossaerts will speak "Of Bulls, Bears, and Crystal Balls." And as the 1900s draw to a close, Robert Neary, Caltech's chief administrative information officer, will attempt to answer the question "The Y2K Problem: Solved?" on November 17. Then, shortly after we find out if he was right, Fred Culick, Hayman Professor of Mechanical Engineering and professor of jet propulsion, will tell us "What Happened in Aeronautics After the Wright Brothers?" on January 12, 2000. All Watson lectures are at 8:00 p.m. in Beckman Auditorium and, as always, are free and open to the public. □

ZAG and Chicken Soup

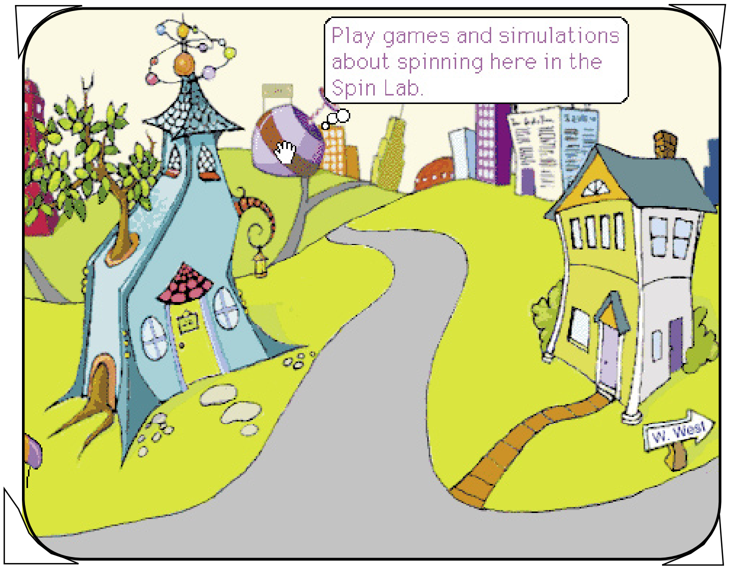
Caltech biologists have determined the three-dimensional structure of a protein that causes fat loss in some cancer patients. The discovery could lead to new strategies for controlling weight loss in patients with cancer or AIDS—and conversely, perhaps new strategies for fighting obesity. The protein is commonly known as ZAG and is found in most bodily fluids. Researchers have been aware for some time that the protein is particularly abundant in some breast cancers. More recently, researchers have discovered that the protein is involved in the wasting syndrome known as cachexia, which is associated with both cancer and AIDS. "This protein has something to do with fat metabolism," says Pamela Bjorkman, professor of biology and associate investigator at the Howard Hughes Medical Institute. Bjorkman and senior research fellows Luis Sanchez Perez and Arthur Chirino (who is also an associate at the Howard Hughes Medical Institute) published ZAG's structure in the March 19 issue of *Science*.

It turns out that ZAG resembles a family of proteins known as class I major histocompatibility complex (MHC) molecules. "MHC proteins have a large groove that binds a peptide derived from a pathogen," says Bjorkman, adding that their picture of the ZAG crystal shows an unexpected blob in ZAG's counterpart of the MHC peptide-binding groove. The blob is "not a peptide, but some organic molecule," she says. "We suspect that it is involved in the function of ZAG. If this compound is involved in breaking down lipids, that is, fats, then maybe you could design a drug that replaces it and interfere with lipid breakdown."

According to Bjorkman, other research has shown that tumor cells seem to stimulate the body to overproduce ZAG, which in turn leads to the breakdown of body fat. Thus, people suffering from cachexia lose body weight not because they don't eat, but because the fat in their bodies is ultimately destroyed by an interaction involving ZAG. Thus if the overexpression of ZAG were disrupted, perhaps by monoclonal antibodies or small molecules that bind to ZAG, the wasting might be stopped, she says. □—*RT*



This rendering superimposes the ZAG structure (red) and the MHC class I structure (green) to show how similar they are. The blue chicken-wire sculpture in the binding groove represents the electron-density outline of the as-yet unidentified organic molecule that binds to ZAG. The ball-and-stick structures sticking into the groove are the amino acids that make up ZAG's binding site.



Above: Whyville Square is the heart of Whyville, containing the site's four original buildings. Clockwise from bottom left-hand corner: Dr. Leila's House, the Spin Lab, the Times Building (in white), and the CAPSI House. (Whyville artwork by Ann Pickard)

THE WHOS, WHATS, AND HOWS OF WHYVILLE

Who can forget the Whos? Residents of Whoville in Dr. Seuss's *How the Grinch Stole Christmas*, the Whos were a close-knit community who loved nothing more than the opportunity to frolic about in celebration.

With that spirit in mind, welcome to Whyville, an interactive Web site that celebrates science education. Based on more than 15 years of science education research by the Caltech Precollege Science Initiative, the Whyville community—located on the Web at www.whyville.net—is designed by CAPSI in conjunction with NuMedeon LLC. The production team includes Whyville founder Jim Bower, professor of biology; and alums Mark Dinan '91 and Jen Sun, PhD '96.

Like CAPSI's own approach to science education, the site's concept follows the idea that kids learn science best by doing it. To this end, the site uses games and activities linked to Dr. Leila's (Leila Gonzalez '79) weekly column in the *Los Angeles Times*, "Caltech Connections for Kids," which appears every Thursday during the academic year in the *Times* Living section's "Kid's Reading Room."

For each topic, Dr. Leila gives background information, interesting facts, and experiments and activities that children (and others) can do at home. Each topic is housed in a separate building within Whyville. The first such building, the Spin Lab, contains activities related to such things as momentum, resistance, and rotational velocity and inertia.

Other buildings include the House of Illusions, constructed for April Fools' Day to show how one's eyes can be fooled by certain three-dimensional images; the *Times* building, which contains current and past "Connections" articles; Dr. Leila's House, where members can look at other members' questions and submit their own; and the CAPSI house, a building for educators that includes links to other educational Web sites. And recently the site added the residential suburb of Myville, where registered citizens can claim a plot of land and build a house that then gets rendered in 3-D.

Citizenship in Whyville is open to anybody. Once registered, members may use all of the site's features and can even win prizes to be used within Whyville.

Whyville and the articles are connected to a set of 10-week science curriculum units developed at CAPSI for grades 7–12. Together they link chemistry, biology, physics, and the history of science. □—*RP*

CALTECH–HUNTINGTON SEMINAR FOUNDED

Caltech has received a $90,000 grant from the Andrew W. Mellon Foundation in support of the newly created Mellon Seminar in Interpretation. The seminar, to be taught jointly by William Deverell, associate professor of history, and Amy Meyers, curator of American art at the Huntington Library, will address the intersection between documentary and visual records in American history. Eight graduate students from across the United States will come to Pasadena in the winter or spring quarter of the upcoming academic year (the dates have not yet been fixed) to take part in the eight-week program. "This is an important step in drawing the intellectual resources of Caltech and the Huntington Library ever closer," says Deverell. "This partnership, which was envisioned by George Ellery Hale 80 years ago, offers exciting opportunities to Caltech students and faculty, Huntington curators and fellows, and scholars from other universities." The program will be overseen by the newly established Caltech–Huntington Committee for the Humanities, which is designed to foster collaborative intellectual and pedagogical exchange between the humanities faculty at Caltech and the curators and readers at the Huntington. □—*DT*

In other science-education-journalism news, Caltech and the Foundation for American Communications (FACS) have launched a national initiative to improve the quality of news reporting on science and technology. The initiative's first program is the Jack R. Howard Science Institute for Journalists, being held at Caltech as *E&S* goes to press.

Electrons of a Different Stripe

It may be that Eisenstein's electrons have accumulated into long ribbons, somewhat like lines of billiard balls lying in parallel rows on a pool table.

Caltech physicists have succeeded in forcing electrons to flow in a way never previously observed in nature or in the lab. Professor of Physics Jim Eisenstein and his collaborators have observed electrons that, when confined to a two-dimensional plane within a layered semiconductor crystal and subjected to an intense perpendicular magnetic field, can apparently tell the difference between "north-south" and "east-west" directions in their otherwise featureless environment. As such, the electrons are in a state very different from that of conventional solids, liquids, and gases.

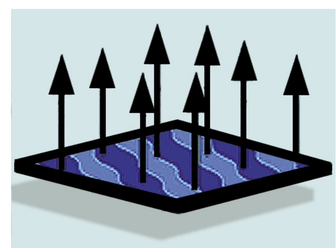
Research on exotic states of electrons is relatively new, but its theoretical history goes back to the 1930s, when Eugene Wigner speculated that electrons in certain circumstances could actually form a sort of crystallized solid. It turns out that forcing electrons to lie in a two-dimensional plane increases the chances for such exotic configurations. "They cannot get out of one another's way into the third dimension, and this actually increases the likelihood of unusual 'correlated' phases," Eisenstein says. Adding a magnetic field has a similar effect by forcing the electrons to move in tiny circular orbits rather than running unimpeded across the plane.

Eisenstein's group has found that a current sent one way through the plane of electrons tends to encounter much greater resistance than an equal current sent at a perpendicular angle. This "anisotropy" only sets in when the temperature of the electrons is reduced to within one-tenth of one degree above absolute zero, which is the lowest temperature a system can approach. Normally, a current flowing at any angle experiences the same resistance as a current flowing at any other angle, because the electrons are dispersed more or less evenly across the plane.

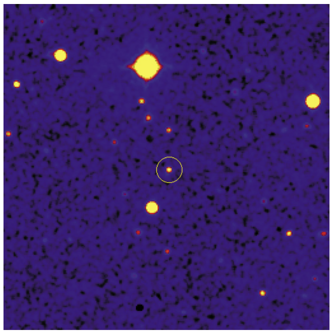
One of the best-known examples of the strange behavior of two-dimensional electron systems is the fractional quantum Hall effect, for which three American scientists won the Nobel Prize in physics last year. (Electrons in such a system essentially act as a liquid that exhibits some unusual properties.) Owing to the laws of quantum mechanics, the electrons' circular orbits exist only at discrete energies, called Landau levels. For the fractional quantum Hall effect, all of the electrons are in the lowest such level. Eisenstein's results appear when higher energy levels are also populated with electrons. While it appears that a minimum of three levels must be occupied, Eisenstein has seen the effects in many higher Landau levels. "This generic aspect makes the new findings all the more interesting," remarks Eisenstein.

It may be that Eisenstein's electrons have accumulated into long ribbons, somewhat like lines of billiard balls lying in parallel rows on a pool table. Something in the ribbon structure overwhelms the electrons' mutual repulsion, allowing them to cram more closely together, while the number of electrons in the spaces between the ribbons is reduced. "There's not a good theoretical understanding of what's going on," Eisenstein says. "Some think such a 'charge-density wave' is at the heart; others think a more appropriate analogy might be the liquid-crystal displays in a digital watch." Another interesting question that could have deep underpinnings is how and why the system "chooses" its particular alignments. The alignment could have to do with the crystal substrate in the wafer, but Eisenstein says this is not clear.

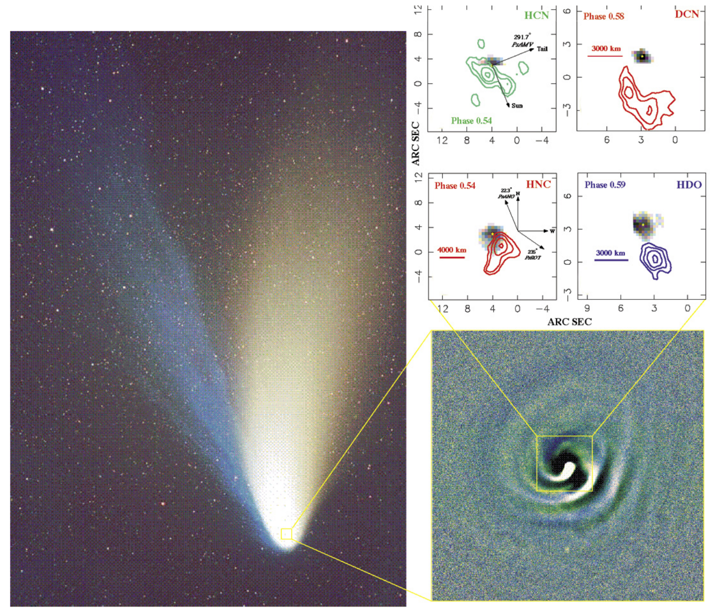
The Caltech group includes postdoc Mike Lilly and grad student Ken Cooper. Loren Pfeiffer and Ken West of Bell Laboratories, Lucent Technologies in Murray Hill, New Jersey, provided the high-purity semiconductor wafers essential to the experiments. □—*RT*



Above: In this view of the semiconductor layer, the hypothesized ribbons of alternating high and low electron density are shown in different colors. An electric current traveling in the direction of the ribbons would meet considerably less resistance than one flowing across the ribbons. The direction of the applied magnetic field is shown by the arrows.



You ain't seen nothin' yet: The circled object, which has a spectrum unlike anything ever observed before, is just one of the first fruits of the Digital Palomar Observatory Sky Survey (DPOSS), now nearing completion. The survey, which covers the entire northern sky in three colors of visible light, will contain information on over 50 million galaxies and about 2 billion stars and will be made available to astronomers worldwide as the Palomar-Norris Sky Catalog. Caltech and JPL are also performing data analysis for the University of Massachusetts' 2MASS (for Two-Micron All-Sky Survey), which is producing comparable amounts of data at infrared wavelengths. Both databases will be available on-line; the first release of 2MASS images (about 6 percent of the final database) went up on the Web in May. For more on DPOSS, see http://phobos.caltech.edu/~george/dposs/. For 2MASS, see http://www.ipac.caltech.edu/2mass.



Zooming in on Hale-Bopp. Left, as seen by H. Mikuz and B. Kambic at the Cnri Vrh Observatory in Slovenia. Bottom right, a computer-enhanced look at the nucleus and its jets, by B. E. Mueller of the National Optical Astronomical Observatory. Top right, OVRO maps of the concentrations of several molecules. The gray blob in the center of each frame shows the nucleus's location.

Comets, Comets Everywhere, But Not a Drop in the Ocean

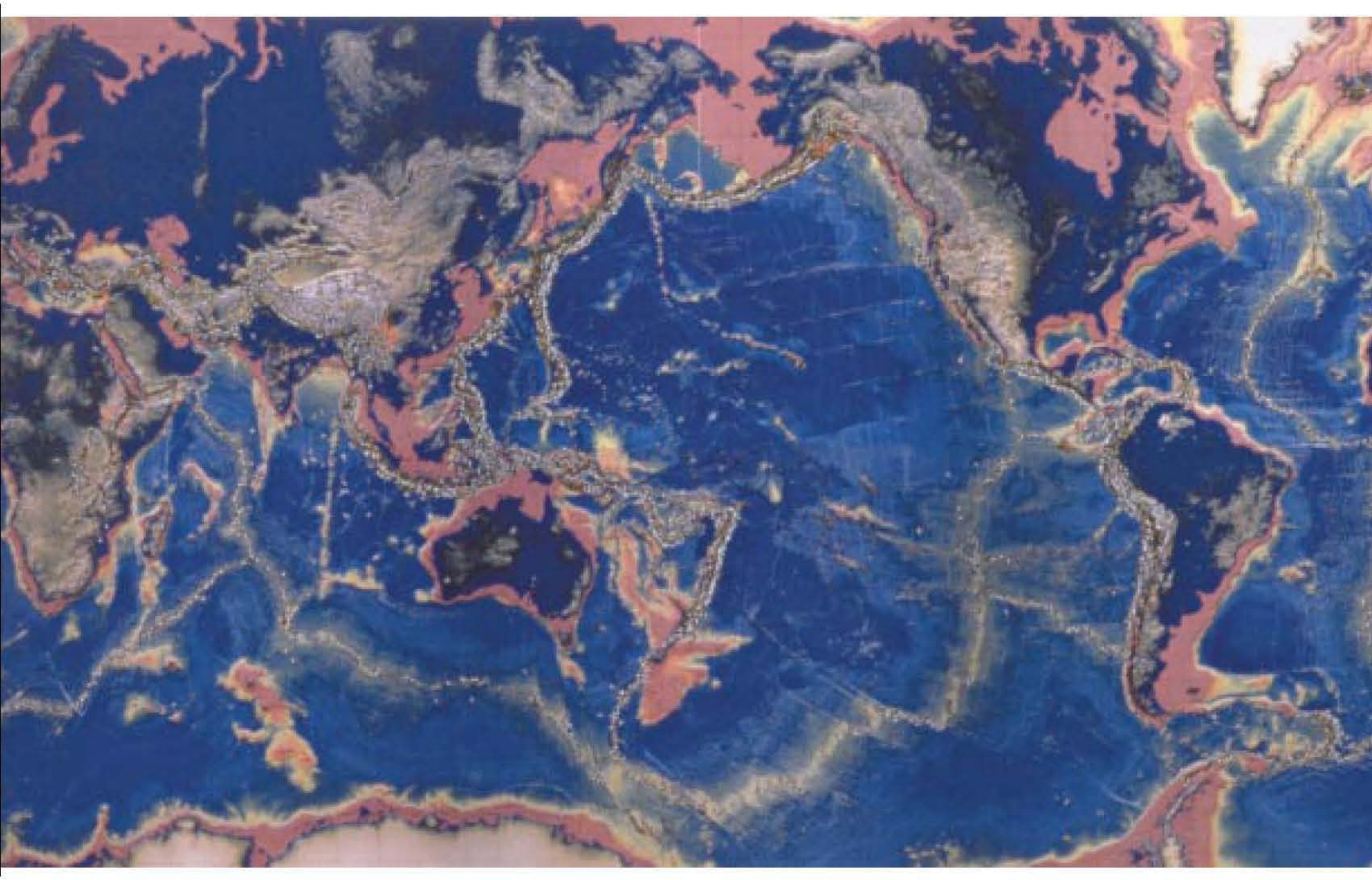
A new study of comet Hale-Bopp suggests that long-period comets did not give Earth most of its water, buttressing other recent studies but contrary to the longstanding belief of many planetary scientists. In the March 18 issue of *Nature*, Professor of Cosmochemistry and Planetary Sciences and Professor of Chemistry Geoffrey Blake (PhD '86) and his team showed that Hale-Bopp contains sizable amounts of "heavy water," which contains a heavier isotope of hydrogen called deuterium. Thus, if Hale-Bopp is a typical comet, and if comets indeed gave Earth its water supply billions of years ago, then the oceans should have roughly the same amount of deuterium as Hale-Bopp. In fact, the oceans have significantly less.

The team, which included grad student Charles Chun-hua Qi, Michiel Hogerheijde of UC Berkeley, Mark Gurwell of the Harvard-Smithsonian Center for Astrophysics, and Professor Emeritus of Planetary Science Duane Muhleman, looked at a form of heavy water called HDO, which can be measured in Earth's oceans using mass spectrometers and in comets with Caltech's Owens Valley Radio Observatory (OVRO) Millimeter Array. Just as radio waves go through clouds, millimeter waves easily penetrate the comet's obscuring coma to see jets of water and organic molecules emitted from the surface of the nucleus within.

The jets are quite small, so OVRO's image clarity was crucial. "Hale-Bopp came along at just the right time for our work," Blake said. "We didn't have all six telescopes in the array when Halley's comet passed by, and Hyakutake was a very small comet. Hale-Bopp was quite large and quite bright, and so it was the first comet that could be imaged at high spatial and spectral resolution at millimeter wavelengths."

The study also showed that Hale-Bopp is composed of 15 to 40 percent primordial material that existed before the sun formed. □—*RT*

The theory of the mantle as a pot on a stove, being heated from below by the core, was by and large invented in England. . . . In this country, however, we like to put ice cubes in our drinks. . . . Perhaps that is why some of us believe that the mantle . . . is cooled from above by ancient continents and subducting slabs poking down into the mantle like ice cubes.



The Inside of Earth: Deep-Earth Science from the Top Down

by Don L. Anderson

This global tectonic map shows plates, volcanoes, and earthquakes, as well as the age of the ocean floor (white lines). This map can be used to infer the tectonic context of volcanoes and volcanic chains. (Prepared in cooperation with David Sandwell, UC San Diego.)

Earth is really several planets. Which planet you see depends on where you view it from. Looking at it from outside, from space, stripped of clouds, you can see that Earth has two quite different hemispheres—a continent hemisphere and an ocean hemisphere. The latter, the Pacific hemisphere, is underlain almost entirely by one gigantic tectonic plate—a continuous chunk of Earth's crust—which is diving under what is called the ring of fire because of the volcanoes that line the plate boundary along Oregon, Washington State, British Columbia, the Aleutians, the Kuriles, Japan, the Marianas, Tonga-Fiji, South America, and Central America. There are also volcanoes in other places: along other plate boundaries on the sea-floor and in island chains throughout the Pacific. One of the unanswered questions in geology is: why are there volcanoes in some places? In my own work, I turn the question around and ask: why aren't there volcanoes everywhere? For seismology tells us that there is a semimolten layer underneath the plate almost everywhere. Something is keeping it down.

The answer has to do with Earth's outer shell, the lithosphere, which is under lateral compression almost everywhere; it's as if it were tied down, keeping a lid on the lava below. Earth has a lot of melt under that outer shell. If the lithosphere were not under compression, lava would be leaking out everywhere, and we would all be in danger of getting covered by lava flows. Arches and the decks of suspension bridges work the same way: take away the lateral compression and they fall apart.

Continents are part of the lithosphere. The continents break up and reassemble every 400 or 500 million years or so. About 750 million years ago, Earth's continental fragments were assembled as a supercontinent in one hemisphere. Another supercontinent formed about 250 million years ago and broke up about 100 million years later. (And I predict we'll have another one 250 million years from now.) During these supercontinent time periods, the opposite hemisphere would have been completely covered by ocean. Now, continents have a very important effect on the underlying mantle; they serve to insulate it. What the planet looks like inside depends on whether a supercontinent is insulating the hemisphere or whether the heat has been allowed to escape through an ocean basin. Seismologists have been trying to see inside Earth to understand how the properties of the planet vary with depth, all the way down to the inner core. We are now trying to determine whether the hemispheres maintain their differences far below the surface, and we are finding that the changes from place to place are as important

Image not licensed for Web use

as the changes from one depth to another.

People have wondered about the inside of Earth for a long time. Dante was the first, in his *Inferno,* to draw internal shells with names. As in the 700-year-old drawing below, he imagined the lightweight sinners—the lustful, the heretics—residing in the outer shells, and the heavyweight sinners—traitors to country, to guests, and to masters—down toward the bottom of what would be the mantle. Satan, the biggest sinner of all, lived in the inner core at the center of Earth.

About 350 years ago René Descartes also proposed a layered Earth, which is very similar to the present views of some Earth scientists. He thought the inside of Earth was primordial matter—stardust, bits of heaven. This primordial-mantle idea is pretty much up-to-date. As it turns out, we now believe the mantle is made up of the same stuff as the meteorites, which are leftovers from the primitive solar system. The question is: does any of this primordial material survive today, deep inside Earth, or was it all melted and separated as Earth grew?

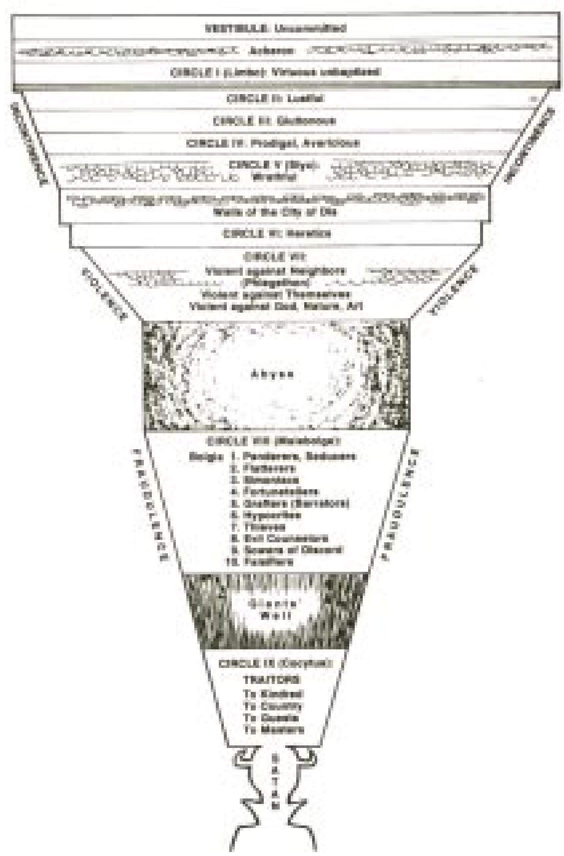
Later in the 17th century, a German Jesuit named Kirschner came up with a fairly sophisticated idea of what was happening inside the planet. He imagined giant tubes of molten rock, lava, and hot air blowing up toward the surface, intersecting tubes of cool, outside air near the outer part of Earth, creating huge volcanoes. Basically, wind was driving the interior fires. He had the idea that if you kept all your volcanoes cleaned out, they wouldn't erupt, so he invented a machine to clean out volcanoes. If this sounds familiar, you may be remembering *The Little Prince,* by Antoine de Saint-Exupéry (1943). The Little Prince was from a little planet with three volcanoes. Every time he left the planet, just to be safe, he would clean out his volcanoes and bank their fires.

These ideas may sound fanciful, but they are remarkably current. In 1971 Jason Morgan and in 1995 Roger Larson (and many agree with them) postulated that the core-mantle boundary—what Dante would call the boundary between hell and nether hell—coughs up giant hot plumes that are responsible for volcanoes at Earth's surface. Morgan's are little plumes, the radius of a volcano, and Larson has megaplumes, the size of North America. So, there's a great similarity between older and newer views of Earth; the very old one isn't based on much data, and I'll get back to the modern one later.

Other ideas about Earth have been fashionable at various times. Studies of the Atlantic hemisphere led to the concept of an expanding Earth: new crust was clearly being formed, but there was no obvious place that the crust was going. Others have assumed from looking at mountain belts that the planet was contracting. If you fly over the Alps, you might conclude that Earth was shriveling up like a dried apple.

Actually, Earth is a very hot planet and always has been. Giant impacts were very important in setting the planet's thermal state, as recent research has made clear. We now think that the moon was generated by another planet hitting Earth when Earth was somewhat smaller. The impact splashed out so much molten magma that remnants of it condensed in orbit and formed the moon. The impact also melted Earth—even if it had already been cooling off and crystallizing, it would have been reset to a molten stage. And

The Little Prince cleans out his volcanoes (above) and Dante stratifies the sinners (right).



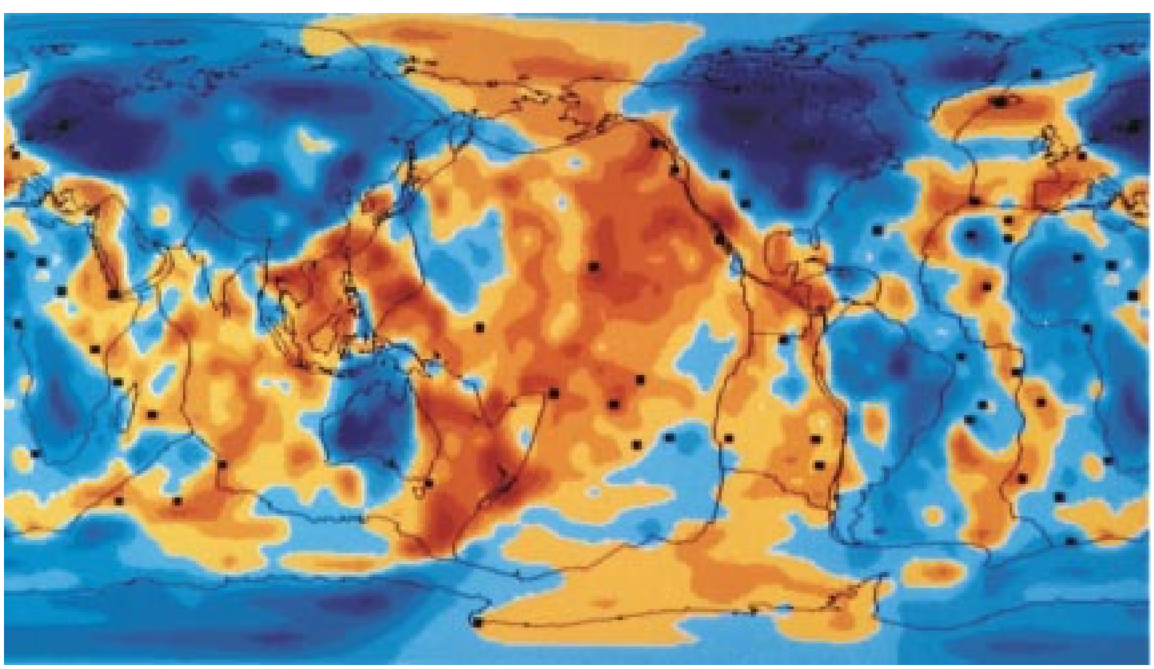
there have been several of these large impacts strewn through Earth's history. The Cretaceous/Tertiary extinction event eliminated a large portion of life on the planet. The impact that created the moon would not only have extinguished all life, if there had been any, but also would have literally liquidated all the rocks and the geology. Earth would have had to start from a hot state again. And our hot planet is livable only because a strong shell holds the hot interior down.

Any way you look at it, Earth started very hot and has been cooling down ever since. Somewhere between a quarter and a half of all the heat currently coming out of Earth is original heat. Although Earth has cooled off quite a bit, the upper mantle, just beneath the outer shell, is held at the melting temperature. It will take much more time before the mantle is completely frozen.

How do we know that it's hot down there? A science known as seismic tomography has enabled us to see inside Earth so that we have a better view than Dante or Descartes. Tomography is similar to medical imaging—we can CAT scan Earth. To get these images, seismologists make use of earthquakes, which send out "rays" that illuminate the interior. We actually measure seismic velocities—the time it takes for a wave generated by an earthquake to travel from the earthquake to a seismic station or a seismometer. It's like a flash of lightning. When lightning flashes, for a brief moment you can see all kinds of things around you, but then the light vanishes and you have to wait for another one to be able to see again. And if you move to another place, you'll see things during a lightning flash that you didn't see with the first bolt. After enough earthquakes and with enough seismic stations scattered over the surface, we can illuminate the planet's whole interior. Today we have a good picture of the interior structure at almost every depth and under almost every place. By comparing these images with global maps of the surface, we can find out why continents drift and what causes volcanoes and earthquakes.

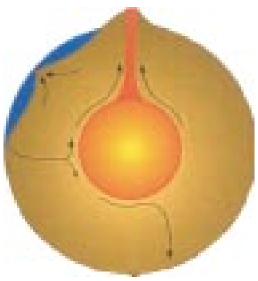
Now, we know that the mantle is made up of rock, although it's under such tremendous pressure and at such a high temperature that it flows, much like glaciers or warm asphalt. We also know that, all other things being equal, seismic waves from earthquakes travel faster in colder solids because they are denser. Seismology has shown us that the speed of a seismic wave doesn't increase with depth in the outer 100–200 kilometers of the mantle in most places below the crust, but actually decreases. That's not what you would expect of a solid that's being pressed under the weight of the lithosphere. But it *is* what you'd expect if the shallow mantle is partially molten. High temperatures and partial melting in the mantle slow the wave down. So this slowing of seismic waves in the outer 100–200 kilometers means that they are traveling through a magma-rich region underneath the high-velocity, strong, cold lid that holds it down. This "magmasphere" exists under oceanic and mountainous regions and around the ring of fire. It may not exist under the oldest parts of continents (the dark blue regions in the map below).

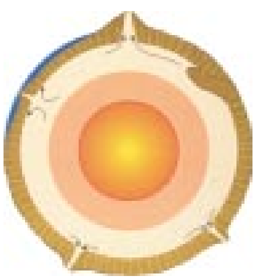
Other research on temperatures inside Earth also points to melting beneath the plates. Estimates of the interior temperature show that it's close to or above the melting point in the upper mantle just in the region where we've found this low-velocity zone. This has likely been the case throughout Earth's history—at least the past 2.5 billion years. Geology professors Ed Stolper and Peter Wyllie, with their colleagues at Caltech, have shown that



This early (1984) Caltech tomographic map shows Earth at a depth of 170 kilometers. The blue regions are centered on the oldest parts of the continents, indicating that they have deep, cold roots. The red regions are mainly in young oceans and tectonically active areas such as California. The Pacific mantle is seismically slow (hot). "Hotspots" (block dots) generally occur above broad, hot regions of the shallow mantle, often along fracture zones or old ridges. (I. Nakanishi, H.C. Nataf, and D. L. Anderson)

Shown below are two extreme views of the sources of so-called midplate, or hotspot, volcanoes. the upper globe shows the plume, or megaplume, hypothesis, in which volcanoes such as those in Hawaii and Iceland sit atop a hot plume that extends to Earth's core.





The lower globe illustrates the view that the upper mantle is hot enough almost everywhere to supply magma through cracks in the outer shell. Most of Earth's outer shell is under compression, but in some places it is being pulled apart, allowing the underlying magma to escape as a volcano.

rocks melt at much lower temperatures than was previously believed. So the sciences of seismology and petrology agree on the likelihood of melting in the upper mantle. Other recent work shows that temperatures in the shallow mantle are higher than commonly assumed.

It's hard to avoid the conclusion that there is magma in the upper mantle. This leads back to my original question: why don't we have volcanoes everywhere? Why does this hot mantle push through in only certain places? In order to answer this question, I'll be discussing two completely different ways of looking at Earth.

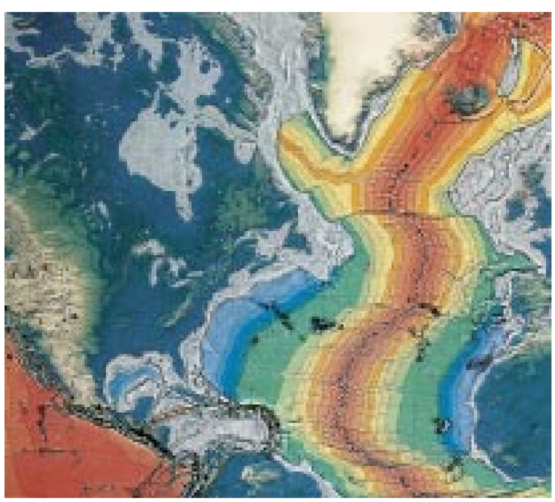
One point of view, the hotspot or plume hypothesis, speculates that plumes of hot mantle come up to the surface from the core-mantle boundary. This hypothesis proposes that the core is heating up the base of the mantle, causing large buoyant plumes to rise, and that every active volcano that's not at a plate boundary is connected to a hot, narrow upwelling that goes all the way down to the core-mantle boundary. This is often referred to as the pot-on-the-stove analogy.

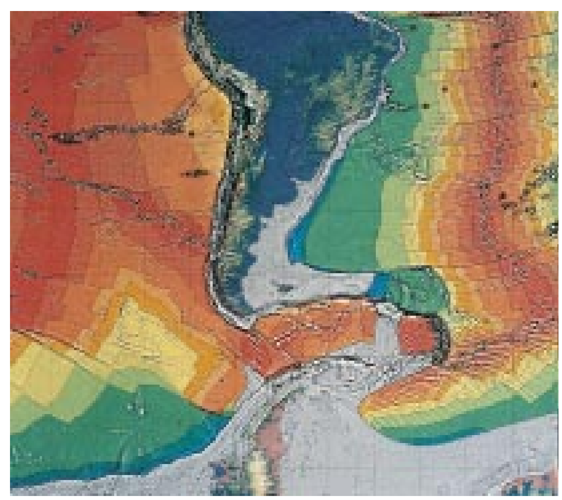
The alternative point of view is that magma, which can be very shallow, comes up through cracks in the lithosphere. In fact, magma can break rocks and make its own cracks, a process called "magma fracture." So Earth scientists have to try to determine which one of these models is true: do we need to import heat from the core-mantle boundary to the top to get molten rock, or do we already have molten rock at the top and just need to make a crack to let that magma out? The question then becomes: do plumes cause the cracks and volcanoes to form? Or do plate tectonics and lithospheric architecture control the locations of cracks and volcanoes?

First, I'd like to explain a little about how plate tectonics works. Tectonic plates are those parts of Earth's outer shell that are under compression. Plates break when they're released from compression and get stretched out; we call this "going into extension." Compression holds plates together; extension allows them to break. For example, the mid-Atlantic ridge is a very large crack in the middle of the Atlantic Ocean, which extends through Iceland and across the North Pole. This crack emerged 180 to 200 million years ago, and as it did, North and South America started to rotate away from Africa. That crack continues on the other side of the world as the East Pacific rise, which cuts through the Gulf of California and then heads due south to Easter Island. These cracks, which are the places where the lithosphere is under extension, control the fate of Earth.

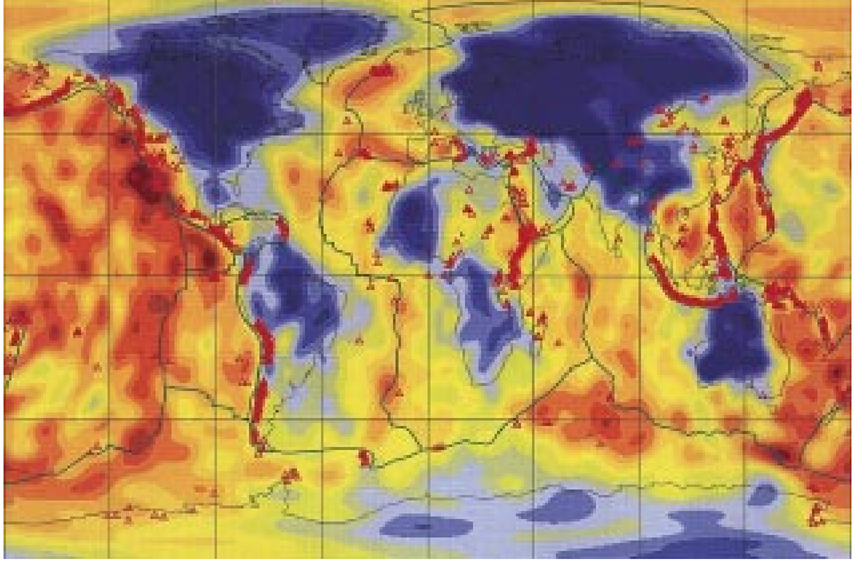
Midoceanic ridges are created by plates being pulled apart. The plate breaks in the middle. It's thin and hot, and new magma comes up through the crack. Then, as the plates continue to be pulled away, the magma freezes and makes new oceanic lithosphere. So the oceanic lithosphere is hot along the ridge in the middle of the ocean, and then cools and gets thicker and thicker, and older and older, as it moves away from the ridge. There's no doubt that the volcanoes along the mid-Atlantic ridge are due to plate-tectonic forces causing tension cracks that then allow the magma underneath to come up through them. When we compared our early tomographic cross sections with geological maps, we found that a seismically slow, very hot region extending down to about 200 kilometers occurred at every crossing of a midoceanic ridge. These hot regions are usually represented by red in our images.

At the other end of the cycle, the lithosphere that has formed at a ridge dives underneath a





These maps of part of the northern hemisphere (left) and southern hemisphere (right) show the ages (colors) of various parts of the seafloor; the youngest seafloor is red, moving to orange, yellow, green, and finally blue in the oldest parts. Earthquakes (black and white circles) and volcanoes (yellow triangles) occur mainly at plate boundaries. (Prepared with David Sandwell.)



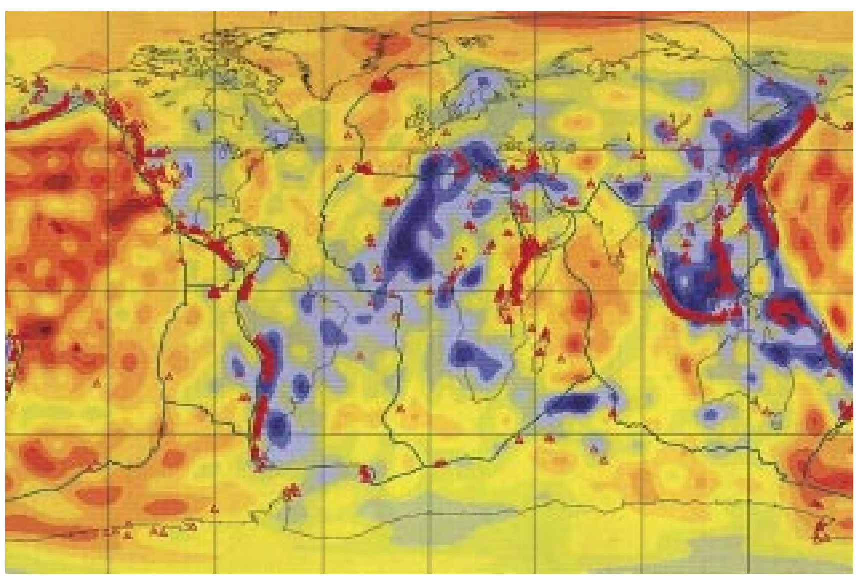
The tomographic map at left of the seismic velocities at a depth of 150 kilometers shows fast, blue regions (cold) and slow, red ones (hot or containing melt). Most of the blue regions are roots of old continents. The most ancient slabs appear as blue in the map below at a depth of 400 kilometers. The red triangles indicate volcanoes. Plate boundaries are shown as black lines. (Courtesy of Hendrik van Heijst.)

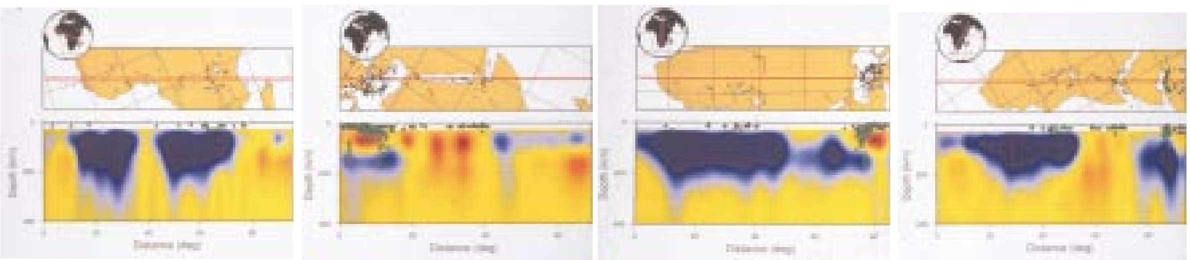
continent in a trench and disappears into the mantle again. These deep-sea trenches, also called subduction zones, encircle the Pacific Ocean. The nearest ones to us are in Central America and off the coast of Washington, Oregon, and British Columbia. The Alaskan coast and the Aleutians are also shaped by trenches, where the plate slides down into the mantle. Because the plate was at Earth's surface, it should be cold when it sinks, and seismic tomography can detect these cold regions (which we usually indicate as blue) going down to 600 kilometers. Numerical correlations show that these slabs may end up in the middle mantle, the mesosphere, between about 600 and 1,000 kilometers depth.

Tomographic images also show that the East Pacific rise extends right under western North America. The mantle under California is just as hot as it is under the spreading ridge to the south, where molten rock is spilling out on the seafloor. In fact, the San Andreas fault is part of the Pacific– North American plate boundary. A rise and trench system once existed off the California coast, but the ridge was overridden by North America. The ridge and trench collided and annihilated each other, and now western North America sits on top of what used to be the East Pacific rise. The tomographic images show reddish regions underneath, which imply temperatures that are very close to or above the melting point. It is only the cold, strong plate under California that is keeping the magma down.

We have also discovered that continents have deep roots extending down to 200 kilometers or so. Every time a seismic wave crosses an ancient part of a continent, we see big blue roots. These deep roots are, in fact, centered on the oldest part of the continents, under Canada, Brazil, Siberia, India, the Baltic states, and parts of Africa. These ancient cores of continents are called cratons, and form the thickest parts of Earth's outer shell. These parts have had longer to grow and longer

Do plumes cause the cracks and volcanoes to form?
Or do plate tectonics and lithospheric architecture
control the locations of cracks and volcanoes?





These four tomographic cross-sections across Africa show the cold roots of ancient parts of the continent (cratons) in blue. The hot (red) upwelling areas are feeding the volcanoes in Ethiopia. (Courtesy of Hendrik van Heijst.)

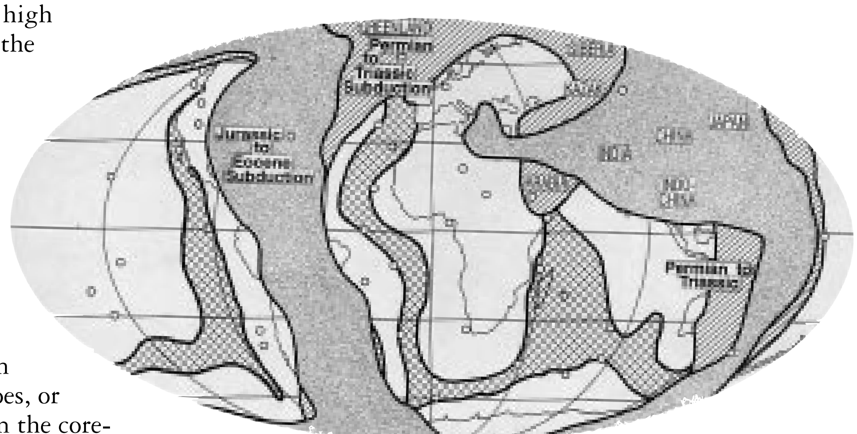
to cool. Seismologists can now find these ancient cores of continents just by looking at their seismometers, without ever looking at a rock or analyzing it in a geochronological laboratory.

The features that we see at the surface of Earth—ridges, plates, continents, and trenches—also show up deep below. Our tomographic maps show us the ancient cores of continents, the thickening of the plate as it moves away from a ridge, and evidence of subduction zones. We also see plate tectonics impressing itself on the fabric of the underlying mantle. We see hot, upwelling mantle under thin lithosphere and cold, downwelling mantle under thick or old lithosphere. We can see mantle being sucked up at spreading ridges.

At depth the whole Pacific mantle has very low seismic velocities and very high temperatures compared to the continents. But volcanic chains occur in only a few places in the middle of the Pacific plate. The question is: is that molten rock associated with what's happening in the middle of the plate or underneath it? Is the Pacific plate under extension there, allowing molten rock to come up in volcanoes, or does a plume come up from the core-mantle boundary? There are few active volcanoes in the middle of the north Pacific. Is there one plume or just one place where stresses in the Pacific plate allow magma to come through?

Where do volcanoes occur in the plate-tectonics scenario? There are very few volcanoes under thick, cold lithosphere. The ancient lithosphere with continental crust on top has two roles. First, it affects the flow in the mantle by causing cold downwellings. But in the case of a supercontinent, the heat can't get out; so it also acts as an insulating blanket, allowing temperatures to build up underneath. The lithosphere underneath old continents is quite strong and able to support itself and is not likely to crack, except along the edges of cratons.

At a depth of 50 kilometers, which is just below the continental crust, cratons show up as high-velocity, or cold, regions. Continental flood basalts were created at various times by the eruption of large amounts of magma, and one such basalt, the Deccan Traps in India, formed 65 million years ago just when the dinosaurs went extinct. Indeed, many of these continental flood basalts happen to correspond to extinctions in the geological record, but what's interesting for tectonics is that they all occur right on the edges of



The globe at right indicates where cold slabs have disappeared into the mantle during the last two supercontinent cycles. These regions should still be cold and show up as blue in tomographic images. The locations of oceanic ridges for the past 100 million years are cross-hatched.

the cratons, the thickest, coldest, and strongest parts of the plates. Somehow, cratons affect the flow of the hot mantle underneath.

At the beginning of this article I mentioned the opposite-hemisphere dichotomy, which I'd now like to pursue a bit further. About 120 million years ago all the continents were joined together in one supercontinent. For some reason it broke

One hundred and twenty million years ago the Pacific plate was new and only a small fraction of its present size. As the surrounding plates were pulled away by sinking slabs around their edges, the Pacific plate grew. Triple junctions occur where three plates join; this is where large oceanic plateaus are constructed. (Courtesy of Paul Heller, University of Wyoming.)

up along weak zones that eventually became the midocean ridges. South America moved away from Africa; North America moved away from Eurasia and Africa. At the same time, on the other side of the world, a series of plates was reorganizing. There were a bunch of plates on the floor of the Pacific Ocean at that point, but one of them, now called the Pacific plate, grew until it eventually filled up almost the entire Pacific basin, and the other plates disappeared underneath the continents that had moved over into the Pacific hemisphere. So the breakaway of North America and the breakup of plates on the other side of the planet are likely related. What probably happened is that the Pacific ridges and trenches, as they collided along the coast of the supercontinent, allowed it to go into extension and break up.

Both the breakup of the supercontinent, which is called Pangaea, and the reorganization of the antipodal ocean plates resulted in vast outpourings of magma. Those in the Pacific hemisphere resulted in what are called oceanic plateaus, California-sized edifices of shallow seafloor underlain by about 20 kilometers of basalt. These plateaus all formed at the boundaries where three plates came together, the so-called triple junctions. As the other continents drifted away from Africa, opening up the Atlantic and Indian oceans, the plates in the Pacific hemisphere kept reorganizing, and the triple junctions jumped around, triggering a new burst of igneous activity each time. In the plume hypothesis, each burst of magma was caused by a plume entering the shallow mantle from below. In the plate hypothesis, it is the new ridges and triple junctions that stimulate a transient burst of magmatic activity.

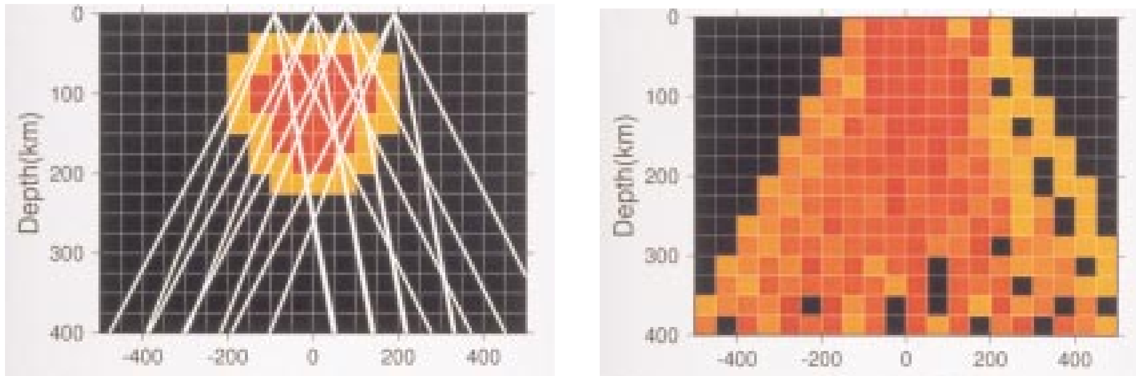
The supercontinent stays together as long as it's under compression, or as long as subduction is holding it together. Subduction zones and deep-sea trenches are also called collision or convergent zones—they compress the continent. But if for some reason we remove that compression, the continent can fly apart. Western North America exhibits a good example of this. When the ridge and trench collided, annihilating each other and forming the San Andreas fault, they removed the force that was holding North America together, resulting in extension. Tension is as important to tectonics as it is to architecture (think of domes, arches, and flying buttresses); tectonics is, in a way, a kind of architecture.

Architecture may be one metaphor for plate tectonics, but I like to use beverages to illustrate the various ideas of what causes the convection currents in the mantle. The theory of the mantle as a pot on a stove, being heated from below by the core (in some experiments, hot fluid is actually poured as from a teapot into the bottom of a tank to simulate mantle convection) was by and large invented in England, where pots on stoves and hot tea are part of the culture. Later, the Australians, who drink a lot of beer, also got interested in mantle convection. Beer has bubbles coming up from the bottom, so the Aussies, too, were sympathetic to this kind of bottoms-up view of Earth.

In this country, however, we like to put ice cubes in our drinks. We also invented the microwave oven, which allows us to heat our American fast food from within; you don't have to wait for it to heat from below like a pot on a stove. Perhaps that is why some of us believe that the mantle is heated from within by the decay of radioactive elements and is cooled from above by ancient continents and subducting slabs poking down into the mantle like ice cubes. Continents themselves can also act as ice cubes to some extent and can cause material in contact with their undersides to cool and slide down.

Heating a glass of tea in a microwave will make it convect by heating it from within; ice cubes in a glass of tea will also cause convection by cooling from above. So we can cool off the mantle from above while heating it from within. This is the top-down hypothesis—the idea that plate tecton-

Seismic CAT scans of Earth's interior can be misleading. The image at the immediate right is a model of a large magma chamber under Iceland; the white lines are rays from distant earthquakes. In optical terms, there is not much parallax with this data—there is no depth perception. When the data from these rays are analyzed (inverted), we get the view at far right, suggesting a deep conical or cylindrical structure extending to 400 kilometers in depth. The "real" structure was all above 200 kilometers. (Courtesy of William Keller.)



ics might be driven, or modulated, from the top rather than the bottom.

We have to decide which one of these metaphors is most accurate and consider other things that are happening. Now we come back to the volcanoes and the question of whether they come from deep plumes or from a shallow part of the mantle. A midocean ridge forms as a crack and then it spreads apart, allowing hot magma to well up and melt. Enormous amounts of magma from large sections of the mantle are involved in this process. Magma can also be found in the ocean islands; they're called ocean-island basalts, which means they're of volcanic origin. Ocean islands represent a trivial amount of basalt compared to the midocean ridge system; they also generally form on older lithosphere. The magmas that rise to become ocean islands have some preexisting crust, some sediments, and various kinds of mantle to go through before they erupt, so chemically they look different from the midocean ridges.

While basalts along midocean ridges are relatively uniform in composition and appear to be little contaminated by sediments, crust, or older mantle, ocean-island basalts are not all the same and appear to be variably contaminated by materials that originated at Earth's surface. Do these various kinds of magmas come from different depths in the mantle? Do we have to go all the way down to the bottom of the mantle in order to get ocean-island basalts?

The contaminants in ocean-island basalts may have been acquired from Earth's shallow layers, but here it gets complicated. A midocean ridge samples the mantle as a steam shovel does: it takes huge gobs all at once and mixes everything that's down there. Since ocean islands and continental volcanoes are much smaller in volume, they sample the mantle more like tweezers. It's something like eating a fruitcake: if you take a big bite of the fruitcake, it tastes like a mixture of all kinds of things, but if you take a pair of tweezers and pick out a tiny piece at a time, sometimes you'll taste a candied pear, sometimes an apple or a raisin or some dough. Each of these would taste quite different from the whole fruitcake. Can this difference in sampling account for the difference in chemistry of ocean islands? Since midocean ridges must process 10 times as much mantle each year as ocean-island volanoes do, they can't afford to be too choosy. Island volcanoes, on the other hand, take small, dainty bites out of the mantle.

Most volcanic islands are far from land, and, since most seismometers are on land, it's difficult to obtain detailed seismic images of them. We can, however, obtain clues from studies of other volcanic regions. For example, a study of Yellowstone by Gene Humphreys (PhD '85; now on the faculty of the University of Oregon) discovered very low seismic velocities indicating hot mantle extending down to about 200 kilometers underneath Yellowstone and its vicinity. But it doesn't go any deeper than 200 kilometers. The Wyoming craton (the equivalent of an ice cube or two) also extends down to 200 kilometers. If Yellowstone were a glass of iced tea, we'd have cold downwellings under the ice, and then the warmer part would come up between the ice cubes. This experiment seems to indicate that at least some volcanic regions have fairly shallow roots.

Another experiment, in Iceland, where seismometers received signals from the other side of the world, revealed what looked like a plume going down to 400 kilometers. This seemed to confirm the deep, narrow-plume hypothesis, but one of my students, Bill Keller, has shown that a very shallow source, less than 200 kilometers in depth, could satisfy the same data. Seen this way, the Iceland image looks very much like the Yellowstone image, and we might have the ice-cube, crack, shallow-mantle explanation again. There are large regions of hot mantle under Iceland, Yellowstone, Hawaii, and most hotspots, but the issue is whether the magma is

When you follow this scenario through, from impact and melting to freezing and recrystallization, you end up with a laminated or layered model much like Dante's.

focused to the volcano by a crack or a plume.

The mantle below 1,000 kilometers looks very different from the mantle at shallow depths and bears little resemblance to shallow lithospheric architecture or geology. It may be doing its own thing, isolated from the yet deeper mantle. The mantle below 2,000 kilometers is apparently a still different world, where violent convection seems to be taking place. Perhaps here the iron core really is acting like a hot stove.

I speculate that the mantle may be divided into three chemically distinct regions—a tripartite mantle, to go along with the tripartite Earth (crust, mantle, core). This is much more complicated than current Earth models, but it doesn't yet approach the complexity of Dante's *Inferno*.

In my conception, Earth started out with a primordial mantle (remember Descartes) that was basically made up of meteorites. But during accretion the mantle melted, and the light stuff ended up on top and the dense stuff ended up down below. Because of very large early impacts, the whole mantle most likely was melted as it was being formed, and the light stuff came to the top along with the elements that preferred to migrate with the melted material, leaving behind a dense lower mantle depleted of its basalt-forming and heat-producing elements. When you follow this scenario through, from impact and melting to freezing and recrystallization, you end up with a laminated or layered model much like Dante's, with the lightweight sinners up on top and the heavyweight sinners down below. With this scenario we can explain the dynamics and chemistry involved in plate tectonics and volcanoes by recycling just the outer part of the planet. Although many Earth scientists think that they are routinely sampling material from just above the core, or even pieces of the core, a consistent picture can be formed by recycling surface materials down to 800 or 1,000 kilometers and then back again. Much of the "contamination" that makes basalts from ocean islands so distinctive in their chemistry—and different from midocean ridge volcanoes—actually leaves the downgoing slab before it penetrates deeper than 200 kilometers.

We are far from converging on a commonly accepted view of the evolution of our planet. Unlike in physics, the end—the final solution, the Grand Unifying Theory—is not in sight. A cold, refractory planet, composed in part of original primordial matter, is one reigning view. Another is that the mantle is homogeneous and material cycles from top to bottom and back. Yet another view holds that volcanic regions such as in Hawaii, Iceland, Yellowstone, and the Galapagos are fueled by hot plumes from the bottom of the mantle.

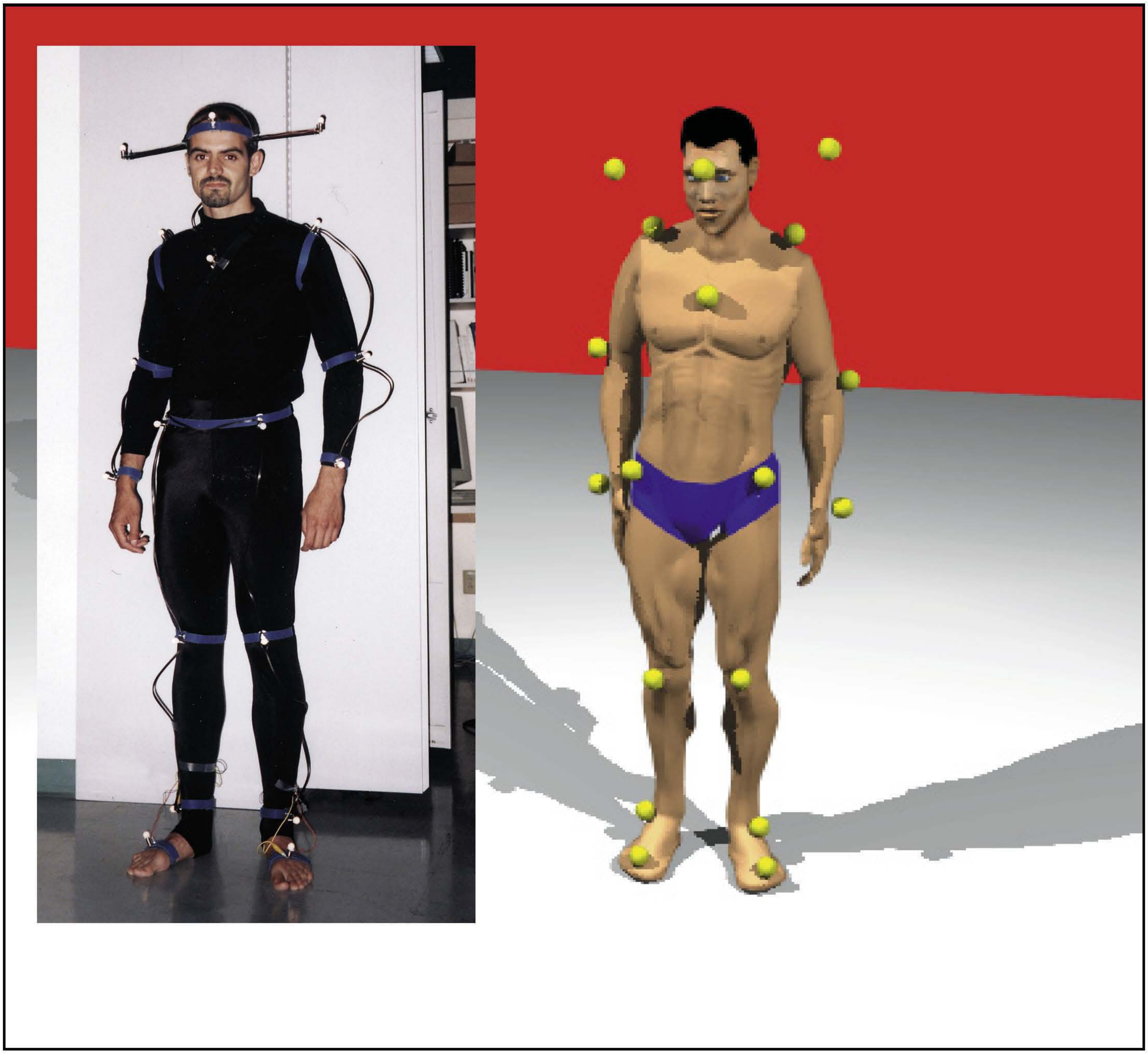
My view is that Earth's accretion destroyed the original material, which then segregated itself into the various layers, sorted by density. The mantle is chemically stratified. The magmasphere produces volcanoes only where the outer shell allows it. Lithospheric architecture and stress in the shell controls volcanism. This is a minority view, but it does at least provide a Grand Unifying Hypothesis. □

Don Anderson presented his iced-tea view of Earth in a February Watson lecture, from which this article is adapted. Shortly before, in December, he was one of nine Americans awarded the 1998 National Medal of Science for his decades-long work on the dynamics of the deep parts of the planet. Anderson first came to Caltech as a graduate student, earning his MS in 1958 and his PhD in geophysics and mathematics in 1962. He joined the Caltech faculty in 1963, becoming full professor in 1968, and since 1989 has held the Eleanor and John R. McMillan Professorship in geophysics. He was director of the Seismological Laboratory from 1967 to 1989. In 1998 Anderson received the Crafoord Prize—the Nobel of geophysics.

PICTURE CREDITS:
10, 17 – Charlie White

The continents and plates visible on the surface of Earth (if it could be seen, as at right, stripped of oceans and clouds) are formed by processes in Earth's interior.

"An image is just a matrix of numbers encoding color and brightness as a function of *x* and *y*," Perona explains. "How do you extract useful information from that mumbo-jumbo? It's not easy. Think of a TV channel that's been scrambled: the information is all there, but you don't *see* anything."



The Machine Stares Back

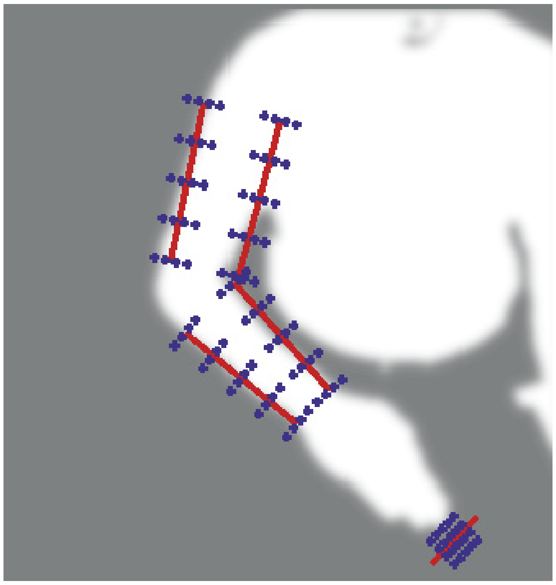
by Douglas L. Smith

In research that gives a whole new meaning to the phrase, "Walk this way," grad student Luis Gonçalves (inset) donned a wet suit and Christmas lights for a midnight stroll in front of a semicircle of video cameras. As long as a light can be seen by at least two cameras, its 3-D position can be triangulated. The data was made cyberflesh with a rendering program called Animation Master (www.hash.com) that included a male model named Jeff. Scaling Jeff's bones up by 115 percent to match the lanky Gonçalves and adding markers in the appropriate spots turned Jeff into virtual Luis. Gonçalves and postdoc Enrico Di Bernardo then wrote a program that took the 3-D positions of Luis's lights and posed Jeff to make his markers match. Given a path to follow, Jeff now mimics Luis's walk.

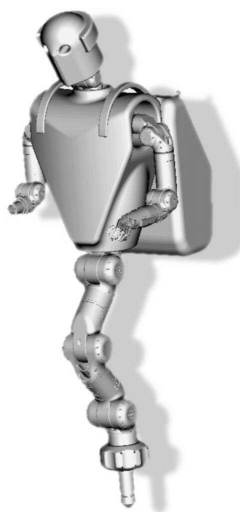
Think how handy it would be to have a computer that could see what you mean. It could read your scrawled notes, or pull complex mathematical formulae off a blackboard from the back of the lecture hall, or interpret a new valve design as you sketch it. If it could follow gestures, you'd be able to manipulate virtual objects without clunky gloves, and walk around in virtual environments without body-sensing suits. You might even be able to make a sign of displeasure and elicit a computer-generated apology, relieving your frustration without the risk of personal injury or hardware damage inherent in smacking your stupid machine upside the monitor when it desperately needs it. Pietro Perona, professor of electrical engineering and director of Caltech's Center for Neuromorphic Systems Engineering (a National Science Foundation Engineering Research Center) is working on various aspects of machine vision that might lead to such things. His lab is exploiting the ready availability of cheap video cameras and frame grabbers, which convert video footage into digital stills, and souped-up PCs that have the horsepower to process those images on the fly. Much of the lab's work would have been prohibitively expensive just a few years ago.

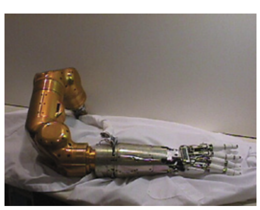
Their research revolves around figuring out what computational processes will impart vision to a computer. "An image is just a matrix of numbers encoding color and brightness as a function of x and y," Perona explains. "How do you extract useful information from that mumbo-jumbo? It's not easy. Think of a TV channel that's been scrambled: the information is all there, but you don't *see* anything." Everything looks like that to a computer, he says—"cameras are cheap and ubiquitous, from automatic bank tellers to freeway traffic monitors to your desktop PC; images flood the Internet, but they're 'consumed' only by humans because, with a few exceptions, nobody knows how to write software that will do something really useful with them." And there are other reasons to design sensory systems for our silicon sidekicks. Computer chips are shrinking but keyboards aren't—at least, not much—so until humans can grow really pointy fingers, computers can't get really small. "And in order to type, or click your mouse, you have to walk up to a computer and touch it. I'd like to be able to deal with it from across the room, or wherever I am, as we do with people." (We also deal with people by speaking to them, and there are Caltech people working on computers that can hear, but that's another article.) "So the key to developing truly portable computers that we can interact with like humans is to replace large, clunky keyboards and mice with tiny cameras and microphones. Given this general long-term vision, if you'll pardon the pun, one needs to start somewhere, and that's where we are."

Back in 1995, postdoc Enrico Di Bernardo, grad student Luis Gonçalves (MS '92), and Enrico Ursella, who was visiting from the University of Padua in Italy, built the first one-camera system capable of tracking the unrestricted three-dimensional movement of a jointed body part—an arm—in real time. (They figured that if they could do an arm, a whole-body tracker would follow fairly easily.) Commercial 3-D motion-capture systems, says Gonçalves, "use multiple cameras, which is a lot easier. The best systems cost about $150,000 and use 16 cameras, and the subject has to wear reflective markers. Also, we deal with a case where the subject is very close to the camera." As you reach toward the camera, perspective causes your hand and forearm to occupy more pixels than your upper arm. Computers don't like it when different parts of the same object keep changing size in relation to one another; other systems work from farther away, where the perspective isn't so pronounced. There are motion-capture systems that don't rely on vision, but you still have to wear something: either magnetic sensors, or an exoskeleton—a



Above: How the computer sees your arm. Once the background (which in this case includes the table the person is sitting at) has been subtracted out, the computer fuzzes the image a bit. The gradient tells the computer how far off it is, minimizing the number of iterations it takes to find the arm. The red lines are the computer's guess of the arm's position; the computer then samples the image at the blue crosses to see how good the alignment is.
Right: A conceptual rendering of NASA's Robonaut, which may be guided by such software. Half humanoid, half scorpioid, Robonaut's "stinger" allows it to attach itself to sockets in the Space Station's exterior members or to the Space Shuttle's manipulator arm. The backpack, which can be changed from mission to mission, holds tools and accessories (think vacuum-cleaner attachments), and can also be used as a mounting point.
Below: Some Robonaut hardware, like this prototype arm, is already taking shape.





fancy knee brace for your whole body, if you will—that measures the angles of your joints. Any system that requires you to strap on anything is invasive, but the Caltech system is noninvasive—no markers are required. "When we started this," Di Bernardo recalls, "there were only three other labs in the world working on noninvasive systems, and they all used multiple cameras. And now a few other people are developing markerless multicamera systems. But we wanted a user with no special equipment to be able to interact with a PC, which we assumed would be sold with just one camera."

As the camera rolls, the computer looks at each frame and finds the person by subtracting a background image shot before the person arrived. The system then uses what's called a Kalman filter, which incorporates a mathematical model of how the object is allowed to move, to figure out the arm's position. "They're usually used for projectiles—you know the laws of physics, so you can estimate a very good trajectory from noisy observations," Gonçalves explains. (In this case, the "noise" includes such things as baggy sleeves that mask the arm's position.) The Kalman filter also enables the system to operate in real time, because the computer only examines the part of the image where the filter predicts the arm must be—if you know the arm is moving up and to the left, for example, there's no point in looking for it in the image's lower right corner. "We process only 900 pixels out of 300,000 in the image."

In 1995, says Gonçalves, the available biomechanical models of human motion "worked under limited conditions. One smooth gesture, say. Not for general movement." So the trio created their own model that described the relative positions and angular velocities of the elbow and shoulder joints. It's a very simple model—two truncated cones with two joints, four rotational degrees of freedom, and no hand motion. It assumed the velocities were the same as they had been in the previous frame, but it incorporated a random-velocity component that allowed it to cope with speed and direction changes. (If you change direction really violently, it may still lose you.)

The filter estimates where the arm is and compares the estimate with the image. The first guess is never dead-on, says Di Bernardo, "so the difference between the two gives you an error measurement. And you input that error back into the model recursively, and it tries to bring the error down to zero." Adds Gonçalves, "You could have an iterative process that keeps repeating until it converges to the best pose at each image, but that's not very efficient computationally. A Kalman filter converges over time, but at each image it does only one iteration, so you don't have to do a lot of computations." The system reliably estimates the arm's position to within five centimeters in all directions, including along the camera's line of sight—the hardest direction to calculate.

> "The original walk was me dying and walking at the same time, and then another night, I pretended I was happy. It learned the happy walk, too, and you can see the difference."

Based on this work, the Perona lab is contracting with JPL to provide the "front end" of a vision-based control system that may be used for Robonaut, a humanoid (from the waist up) robot that NASA is developing to help build the space station. Robonaut is designed to cut down on human spacewalks—it will mimic the movements made by an operator aboard the space shuttle, pantomiming for a camera. So as the operator tightens a virtual pipe with a virtual wrench, or whatever, Robonaut will tighten the real thing. (A pair of TV cameras in Robonaut's head will allow the operator to see what Robonaut is doing.) Says Gonçalves, "NASA didn't want any electromagnetic sensors, because of the potential for interference with other shuttle systems." "They really like the camera-based solution," Di Bernardo adds.

Having demonstrated that they could capture 3-D arm motion without tracking specific features, the research group was ready to take on the whole body. This was a far more ambitious project—there were 14 major joints (not counting fingers and toes), more than 50 degrees of freedom, and an assortment of shapes to contend with. Meanwhile, computer animation had made great strides, and fully jointed human models had become available in commercial graphics packages. But these models didn't help the Kalman filter decide where to look, says Gonçalves. "The models are very good anatomically—the geometry of the skeleton, the range of motion of the joints, the appearance of the surface—but they're static. There's no model for how people move, no synchrony of all the parts. Either a human animator draws a series of intermediate poses, or the model takes data from a motion-capture system with markers. The model doesn't generate the motion."

So in order to acquire information for a lifelike motion model, Di Bernardo and Gonçalves went back to using markers. (Di Bernardo notes wryly, "If we had a noninvasive system that could capture whole-body motion, we wouldn't have to do this project.") Gonçalves painted a bunch of Ping-Pong balls fluorescent orange, strapped them on Di Bernardo with Velcro, and hit him with a black light while shooting video of him reaching to different locations. The duo developed their own learning algorithms to look for recurring features in those motions and automatically generate a model based on those features. There's a demo on the Web at http://www.vision.caltech. edu:80/dibe/research/fg98/reach.html. The demo is just white dots on a black background, but if you click somewhere nearby, the dots reach for that point in an amazingly lifelike manner—looking exactly the way someone wearing a collection of fluorescent Ping-Pong balls in the dark would. The shoulders and hips twist in counterpoise, the opposite knee bends slightly—everything moves, even though only the right arm is doing the reaching. One mouse click on the endpoint completely describes the motion; the computer does the rest. (It's a tribute to our own visual systems that we can see these animated constellations of dots—called Johannson displays—as humans in motion. Grad student Yang Song is trying to develop software that will automatically interpret Johannson displays. "We think we'll be able to extend whatever algorithms we find to the problem of interpreting people moving," says Perona, allowing the Ping-Pong balls or other markers to be dispensed with.)

The model rendered Di Bernardo in two dimensions, the way the camera saw him. In order to graduate to 3-D, the duo used four cameras, decked Gonçalves with Christmas lights, and made a video of him walking around the room. Recalls Di Bernardo, "We'd kick everybody out for the night, move all the furniture, clean up the area, take down the divider, and basically take over the lab."

The walking-around model in its most basic form is a stick figure with a flat, triangular head that looks like a bipedal praying mantis, so they fleshed it out with some off-the-shelf animation software. In either case, the model stands in a box representing the room. You click on the floor wherever you want to step, rather like those learn-to-dance diagrams, and the model walks in your footsteps. Or rather, it plods dispiritedly—not only does it capture Gonçalves's gait, its posture conveys his emotional state as well. "That's exactly how I was feeling," he says. "It was three in the morning. I walked back and forth for a couple of hours with those markers." Wondering how much nuance was available, they went back and tried it again. "So the original walk was me dying and walking at the same time, and then another night, I pretended I was happy. It learned the happy walk, too, and you can see the difference." At this point, the duo realized that they had stumbled across an excellent way to create realistic motions for a variety of purposes, and incorporating the model into the whole-body tracking system got shelved in preference to exploring the model.

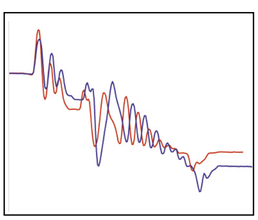
"We still haven't figured out the general model for all motions," says Di Bernardo. "We just have models for particular classes of motions." Adds Gonçalves, "But we can apply our algorithms to learn any action we want—to act like certain people, or act happy, or drunk, or whatever." Gonçalves is graduating soon, so the pair are forming a company, called realMOVES, to animate joystick-driven characters for the video-game industry. Response from game developers is enthusiastic, says Gonçalves. "They said they had never seen something that was computer-generated and interactive look so realistic." The duo is off to a good start—they shared first place (and won $10,000 in seed money) in the second annual 10K Business Plan Competition, run by Caltech's Industrial Relations Center.

Let's shift our focus to the hand. We often pick up a pen in order to convey our thoughts, so why not let the computer watch as we write? Grad student Mario Munich (MS '94) is taking a real-time look at handwriting. Current systems are touch-based, like palmtop computers or the electronic pads at some stores that allow you to sign for a credit-card purchase electronically. (You'll notice, however, that the clerk still compares your signature to the one on the back of the card.) There are other systems that look at handwriting—such as the zip-code scanners the post office uses—but they work after the fact, looking at writing that's already been written. Says Munich, "Ours is the only camera-based system I know of that looks at writing as it's being generated. You could write on ordinary paper while the camera watches, and then throw the paper away. And cameras can be really small. You could have a tiny camera on a wire connected to a credit-card-sized computer. It would be great for airplanes—you'd clip the camera onto the seat-back in front of you, and use the tray table for a desk. It allows for full pen-based interaction with the computer, just as you would with a mouse and keyboard." While collaborators at Bielefeld University in Germany are working on actually reading free-form penmanship (palmtops are still in kindergarten; they can't read cursive script), Munich is working on the underlying problem of seeing the writing.

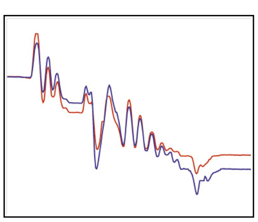
The basic idea is simple. You poise the pen over a predesignated point on the paper for a second or two, to give the computer a chance to find the pen tip. (It's kind of like going to the inkwell before beginning to write with a quill. In fact, a future version of the system will project an inkwell icon onto the paper, and you'll "dip" into the inkwell to start.) The machine beeps when it's ready, and off you go. The computer subtracts out the background paper to create an internal model of what the tip looks like, which it uses to hunt for the tip in subsequent frames. Munich wrote software to measure the tip's position, velocity, and acceleration, and uses another Kalman filter to predict where the tip will turn up next. Again, the system only processes the part of the image it knows the tip will be in, allowing it to run in real time. The computer takes a second look once the pen has moved on, to see if it left a mark. If so, the computer records a "pen-down" stroke (the pen was touching the paper); if not, it's a "pen-up" stroke that the reading program can ignore.

The pen-tip position, velocity, and acceleration data is a mathematical description of a curve, which can be matched against other curves, and Munich realized that he had an ideal system for automatic signature verification—a hot technology although not, as we have seen, a mature one. A machine match isn't yet legal in court, for example; but then, DNA evidence has had a pretty rocky road, too. So he modified a popular signal-matching algorithm called dynamic time warping to compensate for the data being offset in time, meaning that the points from one signature usually lie between the points from the other—for example, the first set might catch a cursive "l" at the top and bottom of the loop, while the second set might catch the midpoints of the ascending and descending strokes. (The system runs at 60 frames per second, so the gaps between the points aren't *that* big, but you get the idea.) He then wrote software to decide if the aligned signatures were close enough to constitute a match, developing more mathematical improvements en route.

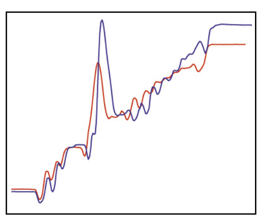
"The hardest part was actually collecting enough examples to train the system," says



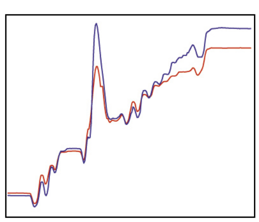
time



time



time



time

Left: Two examples of Munich's signature (top). If you track the pen's vertical motion over time (center), you get this plot. Dynamic time warping (bottom) lines the curves up by squishing or stretching the time axis as needed at each instant to get the best match. The system then measures the vertical displacement between the two traces, point by point, to decide if they are the same. (In practice, a reference signature is derived from compositing several examples.) Right: The same applies to the pen's horizontal movements.

Above: In this shot of Perona's face, the circles mark all the features the computer thinks could be eyes, the +'es are nostrils, and the X'es are nose tips. The computer picks a pair of eye candidates (the correct one, as it happens), and searches the central ellipse for a nose tip and the side ellipses for nostrils.

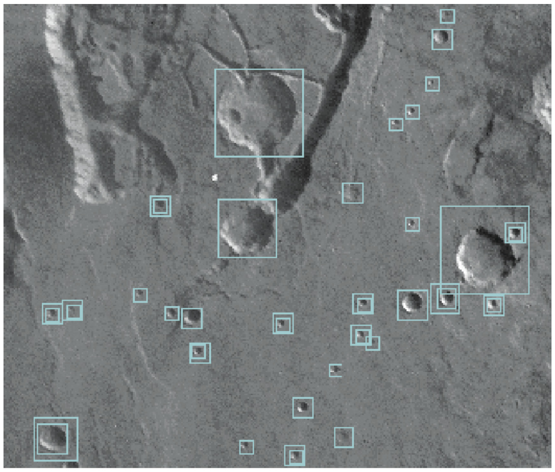
Munich. "Normally, you'd like to have dozens of signatures per person, but there's a limit to how many times you can get your labmates, or someone applying for a credit card, to sign their names for you. I only got maybe 10 signatures each." But he noticed that no two of them were quite the same size, or at quite the same angle, so he was able to generate more by slightly rotating or resizing the ones he had. He could even squash them sideways a bit, as if turning a rectangle into a parallelogram. He used the same strategy to evaluate the system's performance, bulking up the number of real signatures and forgeries until there were enough different samples to be statistically meaningful.

It turns out that for signature verification, it doesn't matter whether the pen is touching the paper. We sign our names so often that it's automatic—a single gesture from start to flourish, what a biomechanician would call a ballistic movement. Half the time we're not even looking. Consequently, the pen-up strokes are just as consistent as the pen-down strokes—and a lot harder to counterfeit. Says Munich, "You can sit and practice a signature from an example, drawing it over and over slowly and carefully, but how are you going to practice the strokes that aren't recorded?" Leaving aside such obvious gaffes as dotting the wrong "i" first, there's the question of rhythm. Since the computer is recording the pen's speed as well as its path, the forger would have to perform in sync with the victim. (Imagine a pair of ice dancers *en duet* in separate TV studios, to be composited on videotape later.) "Many other systems use only the pen-down strokes, so we showed that the full trajectory had a comparable, if not better, performance," says Munich.

But the simplest ID-verification system might be staring you in the face—can a computer know you by sight? Actually, this is really the second of two questions, with the first being, can a computer figure out for itself that it's looking at a face? Consider a security camera scanning a crowded department store at Christmas. Can a computer pull the faces out of the milling crowd, the shifting piles of merchandise, the flashing lights, the gently swaying swags of tinsel, and so on? Only then does it make sense to ask if the computer can say, "Hey! That guy's a known shoplifter!" Volumes have been written about face recognition, but in its most general form it remains an unsolved problem. Besides the usual lighting and perspective troubles that any object-recognition system is heir to, faces are infinitely variable—not only from person to person, but from minute to minute. (Watch a two-year-old making faces in the mirror some time.) So some systems look for very low-level features—the < at the corner of the eye, for example—and measure the distances to other such features. A set of readings that matches average distances on real faces is declared to be a face. Other systems take a high-level approach by looking at all the pixels at once and matching them against a stored gallery of faces.

Mike Burl (BS '87, MS '92, PhD '97), now at JPL; Thomas Leung (BS '94), now at UC Berkeley working with Perona's thesis advisor, Jitendra Malik; and grad student Markus Weber have developed a system that combines the best of both approaches. Their system has a set of high-level feature detectors that independently hunt for such things as the eyes, or the tip of the nose, or the corners of the mouth. Each detector marks all the spots that it thinks could be its feature, and the candidates are then combined in groups to see how they fit. "It starts by looking at the features a pair at a time," Burl explains. "Given a pair of features, it knows where to expect the other ones. So given a potential right eye and a potential left eye, it searches an ellipse between and below them for a potential nose, and so on." If everything falls into place, it's probably found a face; if not, it probably hasn't.

Above: Four out of five ain't bad. The computer can still find Burl's face, even with one eye hidden.



Courtesy H.U. Keller, © Max-Planck-Institut fur Aeronomie, Lindau, Germany.

Right: Comet Halley's nucleus, as seen by the Giotto spacecraft. This is the closest view we've ever gotten of a comet.

Above: Craters may be the most prevalent feature in the solar system. They provide planetary geologists with important clues about a body's surface age, collisional history, and subsurface structure. Unfortunately, labeling craters by hand is slow, tedious, and sometimes even controversial. To help automate the process and provide an objective standard, Burl and colleagues are developing Diamond Eye, a Web-based tool that enables users to look for a variety of objects in large collections of images. In this Viking image of Mars, Diamond Eye has marked prospective craters for human verification. Initial results are promising, but the system is still in development.

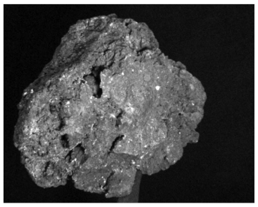
That word "probably" is the key. Other systems make "hard" detections—either something is an eye corner, or it isn't. This system gives "soft" detections, saying, "Gee, this looks pretty eye-like—I'll say 80 percent odds." This is a lot more error-tolerant, as a set of features that didn't score well individually but are correctly positioned can outscore one *really* good eye that doesn't go with anything else. And if the machine finds a few features it likes really well, it will forgive the absence of the others. Thus when Burl covered his mouth with his hand, or tilted a bicycle helmet over one eye, it still picked him out amid the lab's background clutter.

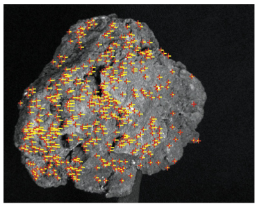
The current version runs on a PC at five frames per second, says Weber. "So every one-fifth of a second, it will find your face. At that rate, it can follow you around. If the system took half a minute to find you, you might be long gone before it decided you were there." This is not only important for security applications, but for fancier notions still to come—if somebody does build an emotion recognizer, for example, it will probably be a computation hog. But if the face recognizer found the face first, and then presented to the emotion recognizer just that part of the screen containing the face (which might only be 10 percent of the image), the emotion recognizer could run much faster because it wouldn't be wasting processing time on extraneous pixels.

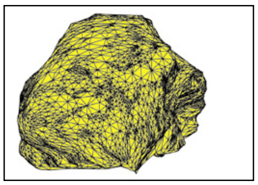
Weber and postdoc Max Welling are now moving on to more general issues. Rather than showing a feature detector 100 eyes, and saying, "Look for these," Weber is showing the computer whole faces and letting it decide what's important, using a statistical method of estimating probability densities. The computer's choices may not be what we humans perceive as essential to "faceness," but by discovering what the computer looks for on its own, Weber hopes to create generic detectors that could be used by anybody to find anything. "You don't want to have eye-detectors and wheel-detectors programmed in," he says, "just for the possibility that you might be asked to recognize faces or cars, because then you would have to have millions of detectors." The latest work in the Perona lab goes straight into the curriculum—Weber is the teaching assistant for EE/CNS 148, Topics in Computational Vision, which this year is covering visual recognition.

At JPL, Burl is developing software to look for and catalog geologic features, such as craters and volcanoes, on Venus, Mars, and elsewhere. At the moment, the software is like an intelligent assistant that can help a human geologist comb through archived images, but Burl would like it to mature to where it could actually fly on a spacecraft, picking targets for other instruments. "Eventually, we'd like to go beyond 'recognizers' attuned to specific objects to 'discoverers' that can decide on their own when something looks interesting," he says. "For example, we might be able to find localized features that are distinct from the rest of the image in some way. When Voyager flew by Neptune's moon Triton, it took human interpreters to discover the ice geysers, something never before seen in the solar system. But it took four hours for the images to reach Earth, and it would have taken another four to send a command back to Voyager. Triton would have been a speck in the rearview mirror by then. So an algorithm that could automatically discover such features and refocus the spacecraft's attention on them would open up all sorts of scientific opportunities. The discovery idea ties back in with the issue of what features are important. If you looked at a lot of faces, you might decide that eyes are interesting, because they are distinctive, localized, and recur in many images. If you looked at a lot of planets, you might decide the same thing about craters."

A spacecraft searching for interesting features on alien worlds also has to figure out where in the world those features are, so that they can be found again on the next orbit. Stefano Soatto (MS '93,





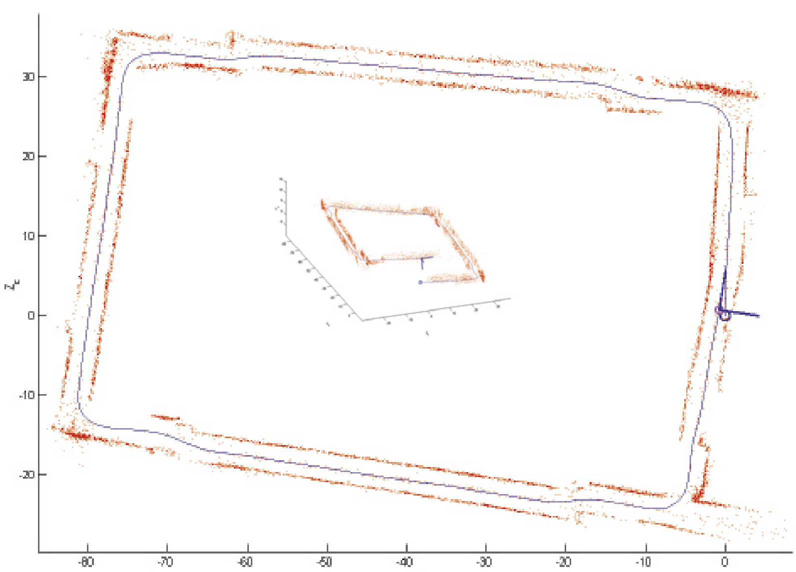


Left: A rotating, basketball-sized rock glued to a dowel stands in for Comet Tempel 1. A typical spacecraft's-eye view is seen in the top picture. In the middle picture, the the computer-selected landmarks are shown as red crosses; the yellow trails are the landmarks' motions since the previous frame. Plotting the landmarks as a 3-D mesh gives the reconstruction shown at bottom. A video showing just the moving points on a black background gives a very convincing illusion of depth, and can be found at http://www.vision.caltech.edu:80/bouguetj/Motion/comet.html.

As *E&S* was on press, NASA canceled Deep Space 4/Champollion due to cost overruns in other missions.

Above: A frame from the video (available at http://www.vision.caltech.edu:80/bouguetj/Motion/navigation.html) Bouguet shot while navigating the Beckman Institute. The blank walls punctuated by occasional doorways and bulletin boards didn't give the computer much to work with, so he printed fat black borders on a couple thousand sheets of paper, which he taped to the walls as landmarks.

Below: In the computer reconstruction of the cart's course, the red dots are the landmarks and the blue line is the cart's calculated path. The scale is arbitrary: five units equals about two meters. Removing the constraint that the motion must be planar (inset) reveals the cumulative errors and turns the lap around the hall into a climb on a spiral staircase.



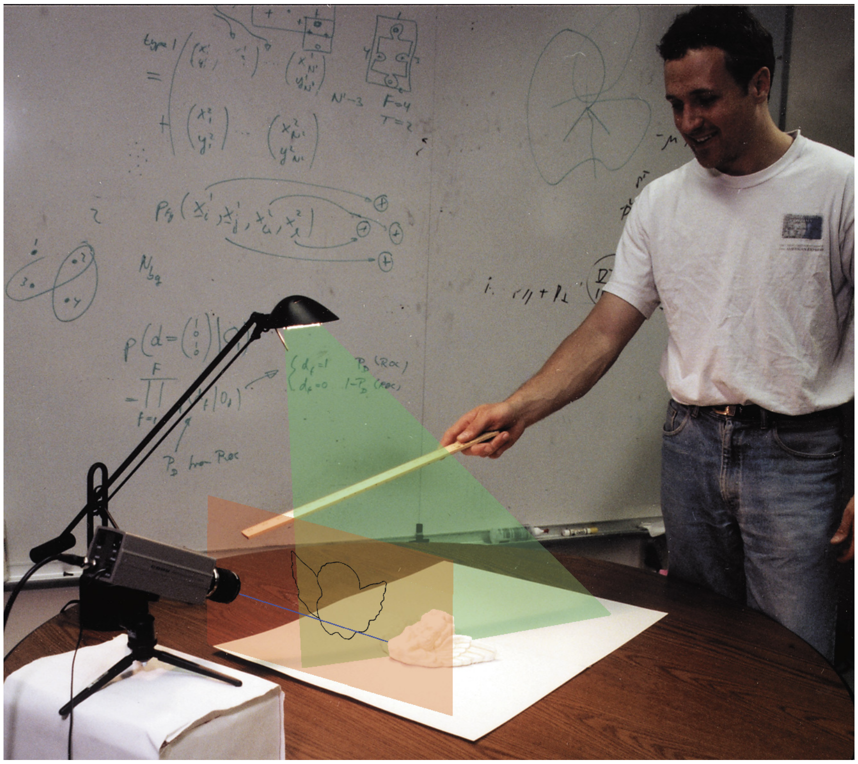
PhD '96) started the project in collaboration with Ruggero Frezza of the University of Padua, and grad students Jean-Yves Bouguet (MS '94, PhD '99) and Xiaolin Feng (MS '96) are carrying it on, working with JPL's Larry Matthies and Andrew Johnson. Their software package is slated to fly on JPL's Deep Space 4/Champollion mission, which is to launch in 2003 and deploy a sample-drilling lander on a comet named Tempel 1 in 2006. In order to steer to a soft landing on a distant comet, says Bouguet, "the response time has to be truly fast. We need an autonomous navigation system, because we cannot rely on control from Earth. And we need a lot of dynamic information: how fast we're going, how fast the comet is rotating, where the landmarks are, and the landing sites."

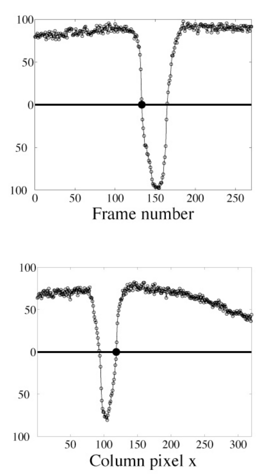
So the question is, if you shoot a movie as you fly by a rock (in their experiments), can you reconstruct its three-dimensional shape using only the information in those pictures? Geometrically, this is basic triangulation, and so-called shape-from-motion estimators have been around since the early 1980s. But there are two problems to be solved before you can triangulate. The first is to figure out how to select landmarks to use as reference points. Bouguet developed software that gives each new frame a quick once-over, chooses surface details that it thinks it can follow, and tracks them automatically thereafter. The second is that, although you know the spacecraft's motion in relation to the solar system, you don't know how the comet and the spacecraft are moving relative to one another. The comet is probably tumbling in some weird way, so your landmarks (and your landing site) will appear to be gyrating wildly. So he wrote a program to extract the comet's motion (also of keen interest to a lander) from the collective paths of the landmarks, and then another program to find the 3-D structure from the computed motion.

But a small, slow-moving object seen close-up looks exactly like an object twice as big and twice as far away moving twice as fast, so Champollion will have accelerometers and range finders as secondary systems. And as the image sequence gets longer and the landmarks are replaced by new ones, cumulative errors creep in. Most researchers finesse this by using one set of landmarks visible throughout the sequence—an impossible feat for an opaque object rotating through 360 degrees. Bouguet got a dramatic demonstration of this problem early on, when he shot a video while riding a cart pushed at a brisk walk by Gonçalves and Ursella through the basement corridors of the Beckman Institute. The Beckman Institute is a hollow square, with level hallways, but the computer reconstructed a rectangular spiral in which the cart rose some six meters over its hundred-meter journey. Bouguet remained unfazed—"I was using a model with as few constraints as possible, so I was not explicitly forcing the motion to be planar. So in my thesis, I propose that M. C. Escher must have designed the building."

In the consumer marketplace, these algorithms could add a whole new dimension, as it were, to home movies—you could plug the vacation videotape you shot in Venice into your computer, and have it reconstruct a 3-D model of the town that your friends could stroll through. Or you could take a scene from your favorite movie, reconstruct it in 3-D, and view it from different angles. Add body-tracking software, and you could even insert yourself into your favorite flick.

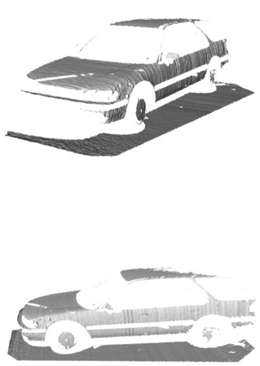
Bouguet continued to refine the navigation system, but on March 6, 1997, something else happened. He was the teaching assistant for EE/CNS 148, which that year covered the burgeoning field of 3-D photography. Besides picking landing sites on comets, there are lots of reasons for wanting a 3-D representation of an actual object in your computer. For example, the new *Star Wars* movie, *The Phantom Menace*, contains dozens of digitally generated aliens, many if not all of whom started as 3-D scans of people. Now when George Lucas scans someone, it's several steps up from pressing your face against the glass of that little flatbed scanner in your office. These scanners cost from fourteen thousand to several hundred thousand dollars, and, in general, use motorized platforms that move very precisely through the beam of a laser striper, while a camera records how the stripe plays over the object's surface. "There are many different types of systems," says Bouguet, "and there are books on the technique of active lighting, as it's called." EE/CNS 148 wasn't quite so high-tech: the class used a liquid-crystal display projector—an overhead projector for your computer screen, essentially—to cast a computer-controlled pattern of parallel lines. But projectors cost money, and you can get a shadow for free. In an informal meeting on the afternoon of Bouguet's PhD candidacy exam, Perona "mentioned the idea of waving a pencil to cast a shadow," Bouguet recalls, "and I saw immediately the geometry of





Above: How to get more 3-D information than you can shake a stick at. The light bulb, the ruler, and its shadow all lie in the same plane (green triangle). The red rectangle is the image plane that the camera sees, so tracing a ray (blue) from the camera back through any point on the shadow's edge in the image plane will lead to the corresponding point on the original object. If the positions of the light bulb and the tabletop are known, finding the shadow's location on the tabletop nails down the plane of the green triangle and thus fixes the three-dimensional coordinates of the point where the blue ray intersects it. Right: In computational terms, the system measures the brightness of each pixel over time (top), finds the maximum and minimum brightness, calculates the midpoint, and notes the frame number where the brightness descends below it. The system then pulls up the corresponding frame (bottom) to find the position of the shadow's edge on the tabletop. The column number of the pixel where the brightness drops gives the edge point's x coordinate; the y coordinate is set by whether the computer is looking at the top or bottom row. A complete description of the project can be found at http://www.vision.caltech.edu:80/bouguetj/ICCV98/.index.html.

Above: This 3-D reconstruction of a plaster cherub took just one pass to generate.
Below: Perona's car.



reconstruction. Basically, everything came as a flash of inspiration."

You literally just set the object on a table and wave your magic wand so it casts its shadow across the object. A few passes gives you a decent picture that, on closer inspection, is as cratered as any comet. But the more passes you make, the smoother the picture gets. And you can change the wand's angle, direction, and speed, or make extra passes over tricky details—as long as both ends of the shadow fall on the desk, the system will work. Scanners need accurate (and expensive) motion control to define the relative positions of the camera and the object, but Bouguet exploits Euclid instead. The lamp, the stick, and the shadow all lie in a plane that intersects the tabletop. Thus the difference between where the shadow lies on the object and where it would have fallen in the background provides the depth.

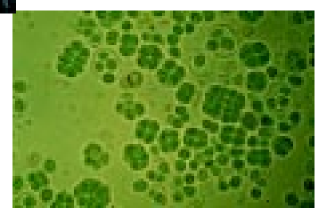
So the computer scans the top and bottom row of pixels in each frame to find the shadow's leading edge in the background at that instant. Another part of the system tracks each pixel individually to see when it turns from light to dark, meaning that the shadow has just reached it. The system notes the time, looks up the background shadow points in the corresponding frame, and triangulates where the suddenly overcast pixel is. Standard methods for finding shadows (and other edges) look for abrupt changes between the relative brightness of all pairs of pixels within a set distance of each other, which takes tons of processing time and can be thrown off by surficial color changes or brightness changes, among other things. But here, says Bouguet, "Each pixel raises its hand, saying, 'I see the edge now! Compute me!' And time is insensitive to variations in the scene." (He later learned that Brian Curless and Marc Levoy at Stanford had proved this mathematically two years earlier.)

A line and a point define a plane, so you need to know where the lamp is. Bouguet uses what he calls the Inverse Thales Experiment, explaining, "Thales assumed that the light came from a known direction, and wanted to measure the height of a pyramid by comparing its shadow to that of a man of known height; we start with a known height—a pencil—and want to locate the light source. And if we do this several times while moving the pencil around, it gives us several lines that converge back at the lamp."

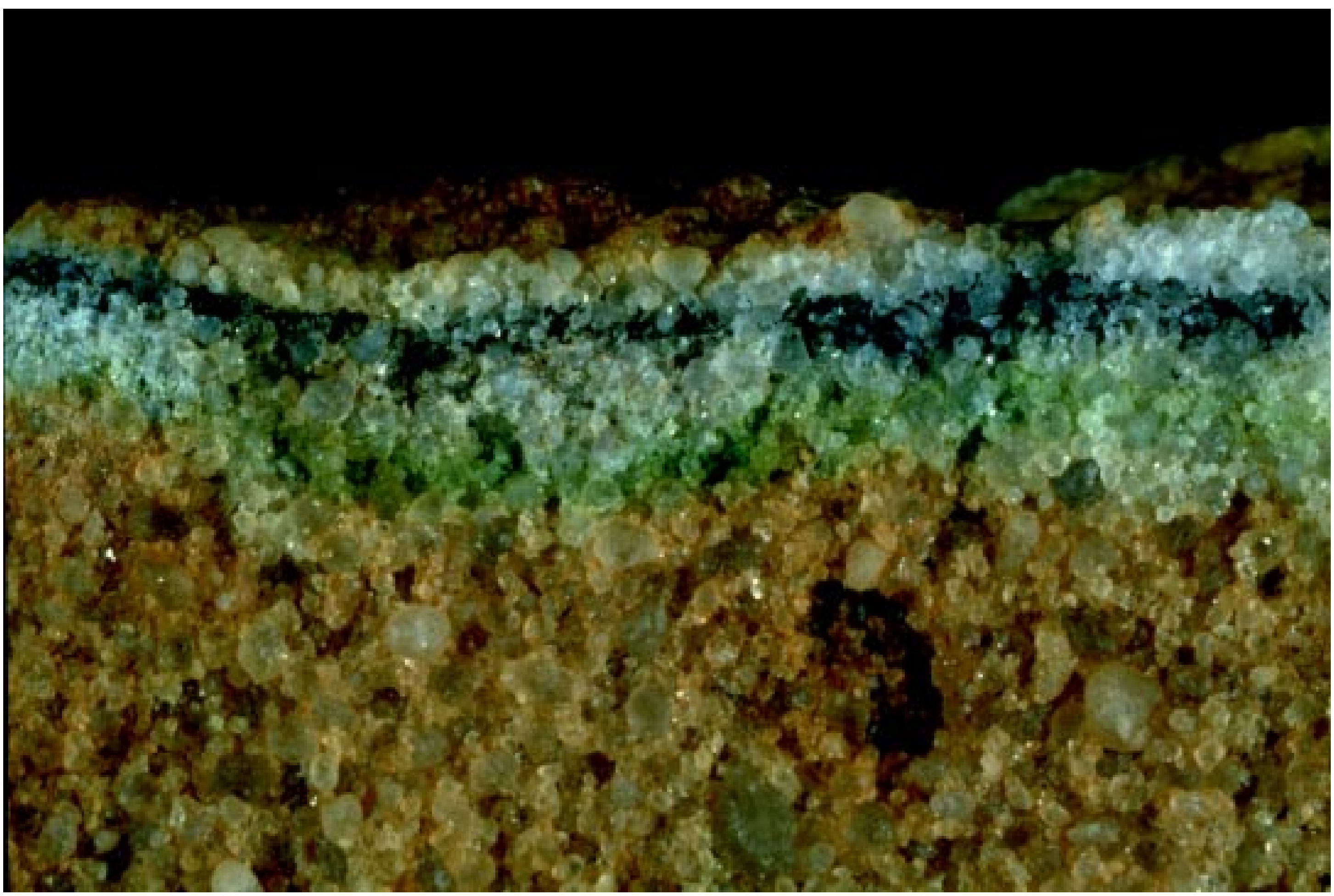
A newer version doesn't even care where the lamp is. If a shadow falls on two perpendicular planes—say the table and the wall behind it—the light source can be derived from that information alone. (Two lines may also determine a plane.) You can scan really big objects outdoors, using the sun, as Bouguet demonstrated by scanning Perona's car in front of a handy wall. It doesn't even matter that the sun moves, because each frame stands on its own. "If you're lazy," says Bouguet, "you could drive a stick in the ground, or even use the shadow of a building, and wait for the shadow to move across the scene."

The method isn't perfect. It can't handle black surfaces, such as Perona's tires, or shiny surfaces, like his windshield, which reflect rather than scatter light—but then, neither will most laser systems. (It does handle nubbly textures much better than the lasers, which require fairly smooth surfaces.) And it only sees what's lit, so areas that are in shadow the whole time don't show up. Nor does the object's back. "That's where active lighting is better," Bouguet admits, "because you can see the object from all angles. We could merge several scans from different viewpoints to get a complete 3-D model with no shadow gaps, but there's still significant work to be done in making sure that the errors don't accumulate and globally deform the structure," the way the Beckman Institute hallway became a spiral staircase. But for many home-computer and Web uses, getting 3-D scans for free sure beats buying one of those fancy systems. The process has been patented, and—surprise!—a company is interested.

But Perona's vision of machine vision goes beyond computers per se—anything with a chip in it is fair game. He foresees "toys that recognize the child that owns them and are able to play hide-and-seek with her, and washing machines that start when we leave the room and quiet down when we come back so as not to disturb us." He then adds a more serious note. If all cameras become "smart," are we on our way to a world where a citizen's every move will be tracked automatically, as George Orwell predicted in *1984*? "The technology to do so will certainly be in place soon, so we as a democratic society had better start thinking about how we plan to regulate what can be done with that information. Being able to interact with a vision-based computer as if it were another human being has a lot of advantages; we just have to make sure that they aren't misused." □



In the high, dry valleys of Antarctica, one of the driest places on Earth, liquid water comes but once a year, and for only a few days. The clever algae, right, (*Hemichloris antarctica*) that make their home in the local rocks manufacture a polysaccharide to keep the water inside to nourish the microbial community, visible in the magnified layers below.



The Search for Extraterrestrial Life

by Kenneth H. Nealson

If I could do it all over again and relive my vision of the 21st century, I would be a microbial ecologist. Ten billion bacteria live in a gram of ordinary soil, a mere pinch held between the thumb and the forefinger. They represent thousands of species, almost none of which are known to science. Into that world I would go with the aid of modern microscopy and molecular analysis.

E. O. Wilson

E. O. Wilson, one of the prominent biologists of our time, has made immense contributions to our understanding of macroscopic life on Earth, and in his book, *The Naturalist*, he expressed the opinion that it is now time to move such thinking to the microbial level. Such thoughts resonate well with my own thinking, since I'm a microbial chauvinist whose career has centered on the definition of life in extreme environments on Earth.

Last year I came to Caltech and the Jet Propulsion Laboratory to set up an astrobiology group, to search for signs of life *off* Earth. NASA has defined astrobiology as everything from the Big Bang to human ecology (and even beyond), and at JPL we have staked our claim in this immense topic in the following way: initially to investigate the earliest stages of metabolic life on our planet and to relate this to the early evolution of Earth. Metabolic evolution, one of the keys that enabled life to become a global phenomenon, was already in full swing more than 500 million years ago. Most of Earth's geology, and many of its atmospheric properties that we still see today, were in place by that time. So, if we want to search for life elsewhere, we must keep in mind that there is no guarantee that a particular planet will have evolved to the same advanced stages we have on Earth. A historical perspective is thus key to developing a strategy for life detection. To put it another way, we must know the early history of a planet in order to frame the search for life properly. One clue we follow in this search is the development of what we call biosignatures—the traces that organisms leave behind. Most of the organisms I will discuss are bacteria, extremely small creatures whose biosignatures can be very subtle. To be a Sherlock Holmes at the bacterial level, one must develop appropriately sensitive and definitive techniques.

Since Earth is the only place where we are certain that life exists, it will serve as our laboratory for the development of the search strategy. The overall strategy is still in its early stage of definition, but a general idea consists of three parts:

1. the development of non-Earth-centric biosignatures for life detection;
2. the testing of these biosignatures on earthly samples to see just how good they are;
3. the eventual use of these biosignatures and tests for the analyses of extraterrestrial samples.

From my perspective as a biologist, this entire process is not only a new endeavor, but also involves asking fundamentally new questions. I don't recall in my entire career anyone handing me a rock and asking: "Is it alive?" or "From this sample, can you prove whether there was ever life on Earth?" Rather, I was given a frog and asked, "How does it work?" "What is it made of?" These days the questions have changed to "What genes are there?" and "How do they function?" But the general problem remains: biologists are trained to study life, not to detect it. Yet detection is what we will be faced with in a few years when samples are returned from Mars. If another planet were, like Earth, teeming with life, this would not be a difficult task. It would be relatively easy to tell that Earth was (and is) alive from almost any distance, and especially so if samples were available for detailed physical and chemical analysis. You could be a very bad chemist and still figure out that there was life on Earth. If the signs of life are subtle or unfamiliar, however, then the task becomes much more difficult. This difficulty is

The author offers thanks for photographs and scientific input to E. Imre Friedmann, John Baross, Henry Sun, Lynn Margulis, Raul Cano, and David Gilichinsky.

If, from space, you had been looking for complex life on Earth, you would have thought it dead until the last few hundred million years; and if you were looking for signs of intelligent life, you wouldn't have found any until 70 years ago when the radio was invented.

demonstrated by the present controversy surrounding the now famous Mars meteorite, ALH 84001. Two years ago, this 4.5 billion-year-old rock was reported to contain evidence for life on Mars. But even now, after extensive research, the jury is still out as to whether the evidence is convincing. The problems stem from many fronts, including the age of the sample, the difficulties in separating indigenous signals from those due to Earth contamination, and the very definition of life and how to prove that it is (or was) present. What this meteorite really has taught us is that we have a lot to learn about how to distinguish life from nonlife.

You would think that, as a group, biologists would be extremely well suited to detect life. Because we understand biochemistry so well, it should be easy to detect life. Indeed, there are molecules that can be detected at very high sensitivity, allowing us to find a single bacterium in a liter of water. If these key indicator molecules are not there, however, it may not be so easy, and we certainly can't depend on the likelihood that life elsewhere would contain the same key molecules that we recognize. The problem then takes on a different aspect: if we rely solely on Earth-centric indicators of life, we may unwittingly fail to detect life that differs in its chemical makeup from our earthly standards.

To this end, our astrobiology group is focusing on what we consider the two fundamental properties of all life: structure and chemical composition, both of which can be detected and measured. Historically, structures are the paleontologists' keys to recognition of past life on Earth. It is structures that characterize life as we know it, and we should expect structures to characterize any new forms of life we encounter. We don't know in advance the nature of the structures or the size scales over which to search, but we do expect structural elements to be associated with any life forms.

In addition, we should be able to recognize these structures by a characteristic chemistry that is easily distinguished from the background chemistry of the planet. On Earth, life is carbon-based with a peculiar and remarkably constant elemental composition (hydrogen, nitrogen, phosphorous, oxygen, carbon, etc.), which is remarkably out of equilibrium with the crustal abundance of our planet. In other words, there is more or less of some elements than would be present if there were no life on Earth. While there are other properties of life that may be measurable (such as replication, evolution, and energy exchange with the environment), and that may leave traces in the geological record, we believe that if life does or did exist, then it will best be detected by the existence of structures and their distinctive chemistries.

In the past few years, a number of new findings in the biological community have greatly changed our appreciation of life on Earth. These new developments, which must be considered in the search for extraterrestrial life, can roughly be grouped into three areas:

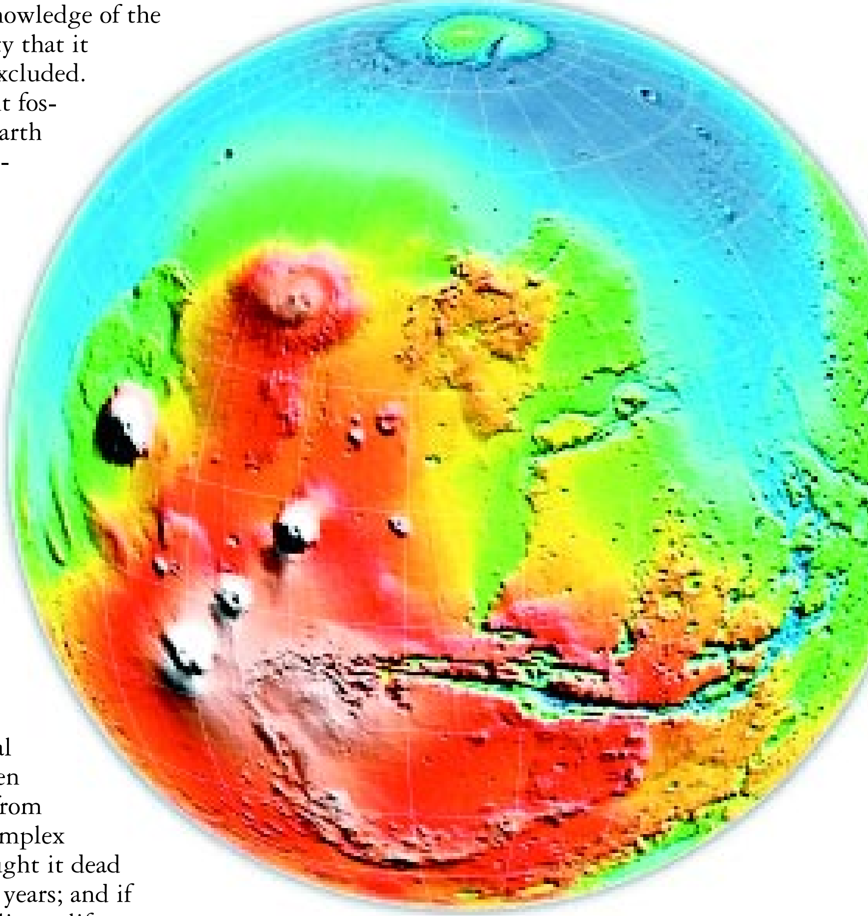
1. the early emergence of life on Earth;
2. its nature and diversity;
3. its toughness and tenacity.

From recent studies of ancient rocks of the Issua formation in Greenland, traces of metabolic activity (carbon metabolism) indicate that life existed on Earth as early as 3.8 billion years ago. This suggests that the invention of life took place rather rapidly, roughly within 200 million years of

Boulder fields in Hawaii (left) and on the moon (right) look equally barren. But don't judge from appearances: in general, earthly rocks, even those in inhospitable environments, are teeming with microbial life.

when the planet cooled and became hospitable for carbon-based life. These results have triggered speculation about life in general (particularly the problems associated with the invention of such complex systems), as well as about the possibility that similar living systems might have evolved on other planets. For example, it is generally agreed that in the early period of planetary development, and up until about 3.5 billion years ago, Mars and Earth may have shared similar planetary conditions. This has led many to posit that life might have had adequate time and the proper conditions to develop on early Mars as well. The subsequent loss of the Martian atmosphere and hydrosphere suggest that extant surface life on Mars would be very unlikely, but, based on our knowledge of the history of the planet, the possibility that it may have once existed cannot be excluded.

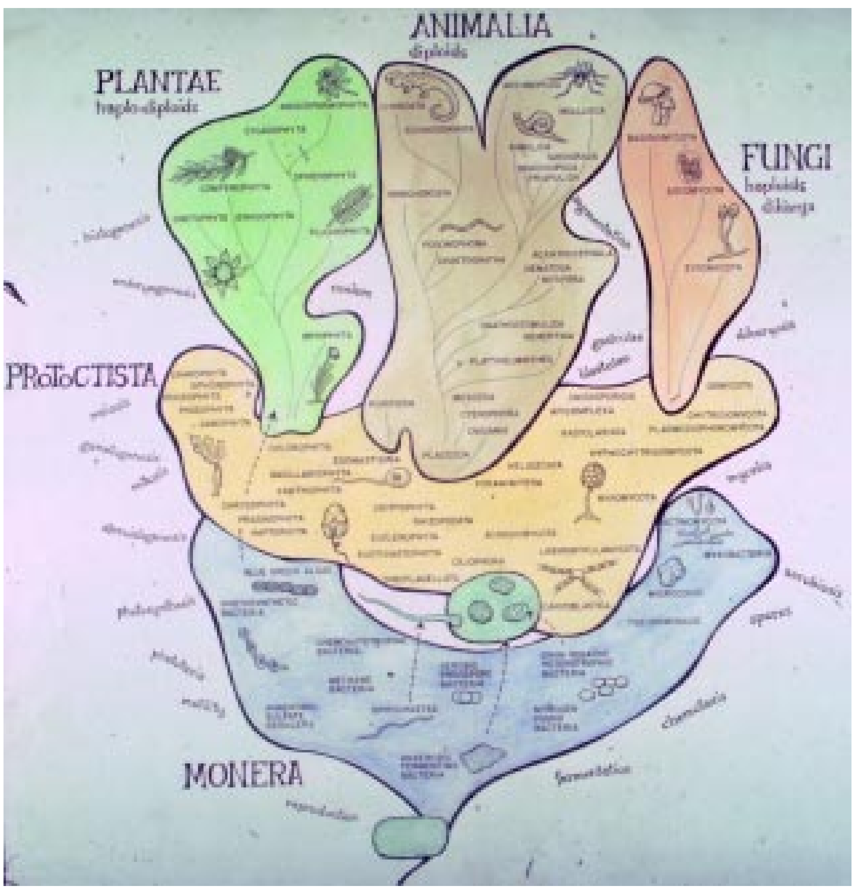
While there are few truly ancient fossils from which to judge ancient Earth life, it seems clear that simple, unicellular life dominated the early Earth; multicellular eukaryotes did not appear until about 2 billion years ago. Complex multicellular eukaryotes—the big organisms like ourselves—were not present until approximately 500 million years ago, when oxygen reached current levels and the Cambrian explosion of life and species (often called the Big Bang of evolution) occurred. From that point onward, Earth began to take on what we would consider a familiar appearance: occupied by plants, animals, and fungi. Before that time, even though it was teeming with microscopic life, by most biological measuring sticks it might have been scored as a rather dead place. (If, from space, you had been looking for complex life on Earth, you would have thought it dead until the last few hundred million years; and if you were looking for signs of intelligent life, you wouldn't have found any until 70 years ago when the radio was invented.) This perspective must be kept in mind when searching for life on other planets of unknown evolutionary age.



Mars (shown at right in a three-dimensional map created recently with data from the Mars Global Surveyor) shared similar conditions with Earth during its early development—up until about 3.5 billion years ago. Might it have also developed primitive life before its water and atmosphere vanished? The Viking Lander, which sampled the Martian surface in 1976 (below, right), found no evidence that life exists now. But was it looking for the right signs that might indicate that life had once existed?

In the past two decades we have moved from a peculiarly eukaryotic-centric view of life to one that openly admits that the small, single-celled creatures that were once ignored play a vitally important role in the metabolism of our planet. The classification of life that most of us learned from our biology teachers contained five kingdoms. It was derived through the work of Linnaeus and others in the mid-1700s, and relied upon observation of the visible features of organisms to give each a name (for example, *Homo sapiens*

The Linnaean taxonomic system (below) classified forms of life according to features that could be observed: legs, antennae, seed pods, etc. Because they exhibited more visible diversity, the plant, animal, and fungi kingdoms are at the top of the tree. Below them are the protists—the amoebas, parameciums, and the like, and bringing up the bottom are the single-celled bacteria, or monera, thought relatively unimportant in the days before powerful microscopes.



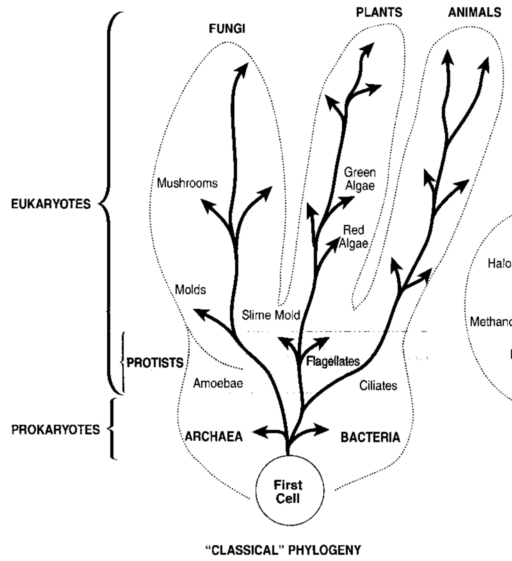
I refer to these organisms [prokaryotes] as the Timex watches of the living world—they're simple; they're rugged; they don't break; you can drive cars over them; it's hard to get rid of them.

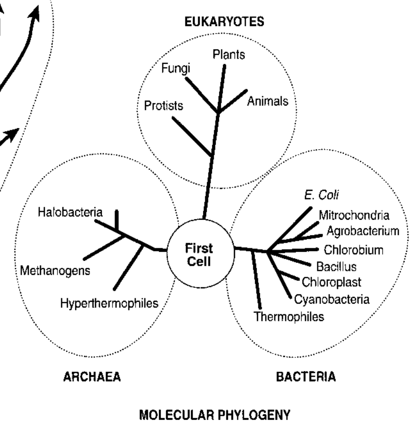
for humans), and to group organisms of similar appearance together. The diagram shown at left is referred to as a phylogenetic tree, which illustrates the presumed evolutionary progression—which groups preceded which in time.

Largely because of the nature of the tools available (human eye, hand lens, and later, simple microscopes), it is not surprising that such trees were dominated by the macroscopic, many-celled eukaryotes such as the fungi, plants, and animals. The tiny eukaryotic protists (amoebae, paramecia, etc.), being visible but not understood, were relegated to the next-to-the-last rung of the ladder, while the prokaryotes (bacteria) were handily put at the bottom where they could be acknowledged but not seriously so. This entire approach was reasonable at the time, in the sense that structural diversity was driving classification, and the single-celled, anucleate prokaryotes have little that is comparable to the structurally and behaviorally diverse larger organisms.

This view of the biosphere changed dramatically in the last decade with the advent of molecular taxonomy and phylogeny. The basic idea behind this approach is that there are some molecules common to all earthly life (16 S ribosomal RNA, for example), and that, if one could sequence such molecules and compare the sequences, it might be possible to use this chemical information to compare all life, even that which can be seen only with a microscope.

We now had a way of putting numbers on the evolutionary tree of bacteria. The germ of this idea is actually decades old, but it has become feasible only recently with the development of new techniques in sequencing nucleic acids and the use of this information for comparison of organisms. This approach, called molecular phylogeny and pioneered by Karl Woese of the University of Illinois, has completely overturned the way we look at life on Earth. Instead of five kingdoms, four of which are eukaryotic, we now recognize three kingdoms—and two of them are *prokaryotic*. Even more dramatic, however, is the realization that the three formerly dominant kingdoms (plants, animals, and fungi) are actually clustered at the end of the eukaryotic assemblage, and display only a modicum of genetic diversity. Based on the distances along these phylogentic branches, the genetic distance between a methanogenic bacterium and *E. coli* (the common colon symbiont of humans) is far greater than that between man and a slime mold. Apparently, it is possible to achieve structural and behavioral diversity (traits that have appeared only in the last 500 million years) while remaining genetically quite homogeneous. This idea frightened those who were used to the classical view, but it shouldn't be so astonishing. Given that multicellular eukaryotes evolved only recently, and that for nearly 3 billion years the prokaryotes dominated the surface of the Earth, we should not be sur-





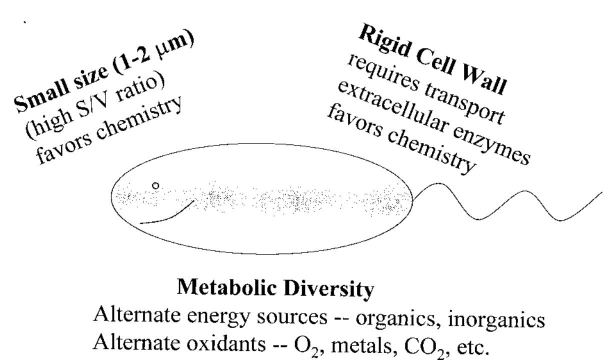
The advent of molecular taxonomy and phylogeny changed the "classical" picture of eukaryotic dominance dramatically. Based on comparison of RNA sequences among organisms, the prokaryotes now occupy two separate kingdoms of their own and display far more diversity among themselves than exists between animals and fungi, which are now lumped together at one end of a branch.

prised that the bulk of the apparent genetic diversity on the planet resides in the latter.

The third critical feature of life on Earth deals with the toughness and tenacity of life. In the illustration below, I have delineated some of the key properties that distinguish the prokaryotes from their more complex eukaryotic cohorts. The eukaryotes are defined by the presence of a nucleus and nuclear membrane in their cells (eu = true; karyon = nucleus), and in general are characterized by complex structures, complex behavioral features, and simple metabolism. Their metabolism is oxygen-based respiration of organic carbon, and the sizable energy yields from this process are used to support their complex structural and behavioral investments. Basically, plants make the organic carbon via photosynthesis, and animals eat the plants (and other animals), leading to the kind of complex communities we easily recognize under the general heading of predator-prey cycles. The very existence of complex structures (both intracellular organelles, and multicellular tissues and organs) renders the eukaryotes sensitive to environmental extremes often easily tolerated by their structurally simple prokaryotic relatives. Above 50° C, it is almost impossible to find a functional eukaryotic cell, for example. Eukaryotes are not tough; put them in boiling water and they soften up right away and you can eat them.

On the other hand, the prokaryotes are the environmental "tough guys"—tolerant to many environmental extremes of pH, temperature, salinity, radiation, and dryness. I refer to these organisms as the Timex watches of the living world—they're simple; they're rugged; they don't break; you can drive cars over them; it's hard to get rid of them. A number of fundamental properties distinguish them from the eukaryotes. First, they are small—they have optimized their surface-to-volume ratio for the most efficient chemistry. On average, for the same amount of biomass, a prokaryote may have 10 to 100 times more surface area. Thus, in your own body, whose mass may be composed of a few percent bacterial biomass (as gut symbionts), the bacteria make up somewhere between 24 and 76 percent of your effective surface area. (This means that most of the chemistry being done inside you is not being done by you but by your bacteria.) For many environments, such as lakes and oceans, where bacterial biomass is thought to be approximately 50 percent of the total, the bacteria make up 91 to 99 percent of the active surface area, while for anaerobic environments, where the biomass is primarily prokaryotic, the active surface areas are virtually entirely prokaryotic. In essence, if you want to know about environmental chemistry, you must ask the prokaryotes.

Prokaryotes have rigid cell walls, which preclude life as predators. They are restricted to life as chemists and do their metabolism via transport and chemistry. This is in marked contrast to the eukaryotes, whose cells are capable of engulfing other cells. Because prokaryotes have a rigid cell wall, they can't engulf other organisms. So they're put into an evolutionary state in which there is no advantage to getting bigger. The engulfing eurkaryotes, however, have a tendency to get



The word extremophile has crept into our vocabulary in the past decade, coined to accommodate organisms that are resistant to, and even thrive in, extreme conditions. These extremophiles can be resistant to chemical (pH, salinity), physical (temperature, dryness), or metabolic extremes.

bigger and bigger; obviously, if you can get larger than the organism next to you, you can eat it. If it were an advantage for the prokaryotes, they would be big. They've had 3.5 billion years to do it, and, by God, they'd be BIG. They would have figured it out.

The full effect of such evolution is seen in the genomic analyses of prokaryotes, where it is common to see 25 percent or more of the total genome involved with uptake, transport, or other membrane- or cell-wall-related processes. Eukaryotes, on the other hand, devote much of their DNA to development, regulation, differentiation, or even duplication. If the prokaryotes are the chemists, the eukaryotes take on the role of the biologists.

Prokaryotes are metabolically very diverse, while the eukaryotes are quite restricted in their metabolic abilities. The prokaryotes have developed a metabolic repertoire that allows them to utilize almost any energetically useful chemical abundant on Earth. Being opportunists, these ingenious chemists have simply harvested every worthwhile corner of the chemical market, learning to utilize both organic and inorganic energy sources. Among the major sources of energy available on Earth today, eukaryotes exploit only light and organic carbon, mainly in the form of glucose. These eukaryotes were smart; they developed a very good fuel. And they use the best oxidant, molecular oxygen, to "burn" that fuel. In marked contrast, prokaryotes have figured out how to derive energy from all sorts of combinations of inorganic fuels (such as hydrogen sulfide, nitrogen, or iron) and anaerobic oxidants—even carbon dioxide, which is the worst oxidant of all. If there is energy in any such fuel/oxidant combination, some microorganism will find it. While eukaryotes have sacrificed metabolic diversity for high energy yield, the prokaryotes occupy the diverse, lower-energy habitats. It's not easy growing on hydrogen sulfide, but this metabolic diversity has served them well.

But what about their toughness? In the past, most people interested in bacteria were trained in medical schools. There you study *E. coli* and the pathogenic bacteria that live in the wonderfully rich environment of our bodies. Of course, these bacteria are not very tough and versatile because we give them everything they want. But the word extremophile has crept into our vocabulary in the past decade, coined to accommodate organisms that are resistant to, and even thrive in, extreme conditions. These extremophiles can be resistant to chemical (pH, salinity), physical (temperature, dryness), or metabolic extremes. And it is seldom in nature that an organism encounters just one extreme. For example, under high temperatures, it is common to find anoxic conditions, because oxygen is not very soluble in hot water. Furthermore, due to high evaporation rates, warm systems are often associated with high salinity. Desert ponds often exhibit high pH and salinity, since evaporating water and the minerals trapped there interact to produce extreme conditions.

The most notorious extremophiles are perhaps those associated with high-temperature environments—bacteria capable of growth at 100° C and above. The maximum temperature of any hyper-

Some bacteria love extreme salinity. The red halobacteria trapped in the salt crystal below are responsible for the color of the salt ponds near San Francisco (below, near right) and the Dead Sea mounds (far right), where a different species has been bleached by the sun.

Alkaline Mono Lake (below) combines high salinity with a pH of 10 or higher—like lye. A peek under the edges of the carbonate tufa towers reveals a green layer of cyanobacteria (left) hiding from the sunlight.

Too-hot-to-handle rocks from recently erupted Mount St. Helens were home to vast communities of thermophiles growing happily on volcanic sulfur.

thermophile is about 115° C, well above the boiling point of water; these organisms can be grown only under pressure where the water is stable and will freeze to death at temperatures as high as 80° C, temperatures that would result in severe burns to humans. Not too long after Mount St. Helens erupted, a group of us was allowed into the area wearing asbestos shoes and protective clothing. We picked up rocks that were 65 to 85° C—too hot to handle with our bare hands. But when we looked at them in the scanning electron microscope, there were wall-to-wall bacteria growing on hydrogen sulfide and sulfur coming up out of the volcano.

We know of bacteria that live in saturated salt brines (the red halobacteria, for example, which are trapped in mounds in the Dead Sea), and at pH values as low as minus 3 and as high as 11. The eukaryotes, on the other hand, are in general much more restricted in their ranges of tolerance.

One of the strategies of life that often emerges when things get tough is an endolithic lifestyle—the ability to associate with rocks, either on or just under the surface. In California's alkaline Mono Lake, for example, we can see that the tufa mounds that dominate the alkaline lake, and which appear to be dead, are teeming with life. A few millimeters under the rock surface are populations of cyanobacteria that hide from the intense sunlight, positioning themselves for optimum growth in the now-filtered light. A similar situation occurs in many desert soils, where the photosynthetic microbes are found under the surfaces of rock layers.

Bacterial communities have also been found in the high, dry valleys of Antarctica, where liquid water can be found on only a few days a year. About 20 to 30 percent of the rock surfaces have a considerable amount of color in them, and when you crack these rocks open, inside is a well-developed microbial community that manufactures a polysaccharide, which forms a layer in the rock to keep the water inside. These microbes can survive all year-round just waiting for the first thaw. On the few days when there's liquid water, these bacteria have some of the highest metabolic rates that we know about; during the rest of the year their metabolic rate is effectively zero.

In pursuit of other extremophiles, let us return to the issue of metabolic diversity. Given that eukaryotes are almost entirely limited to growth on organic carbon with oxygen as the oxidant, any set of conditions in which organic carbon or oxygen are absent constitutes an extreme environment and is a potential life-threatening situation. For the prokaryotes, however, such environments are simply opportunities to exploit the environment via a different nutrition. This might be called metabolic extremophily. The very existence of such diversity forces those of us hunting for life to include such extreme habitats in the search, and to broaden the definition of life to include metabolic abilities that a few years ago might have been summarily dismissed. The ability to grow on energy sources such as carbon monoxide, ferrous iron, hydrogen sulfide, or hydrogen gas (my personal favorites are the bacteria that "breathe" iron and manganese) implies that bacteria could

The core at right drilled from the Siberian permafrost (below) has been frozen for perhaps a million years or more. Yet enormous colonies of ordinary bacteria that aren't even particularly fond of the cold have managed to thrive.

Bacteria entombed in the stomachs of insects petrified in amber (right) for 10 million years can be revived.

PICTURE CREDITS:
30 – E. Imre Friedman;
32, 33, 39 – NASA;
34 – Lynn Margulis;
37 – Henry Sun, John Baross; 38 – Raul Cano, David Gilichinsky

inhabit worlds not heretofore considered as candidates by most scientists seeking extraterrestrial life, and must now be included in any search strategy that is designed.

A final point regarding the prokaryotes relates to their tenacity and ability to survive for long periods of time. There are many examples of bacteria being revived after long-term storage, but perhaps none more dramatic than those from the Siberian and Antarctic permafrost, where soils that have been permanently frozen for 3 million years or more have yielded copious numbers of living bacteria. We have obtained samples from David Gilichinsky and his colleagues from Puschino, Russia, who have been drilling in such sites in Siberia and Antarctica for many years now. It is not unusual to find 10^6 to 10^7 viable bacteria from each gram of permafrost. These are not cold-loving (psychrophilic) bacteria that have adapted to these freezing conditions, but simply mesophilic organisms that usually thrive in moderate temperatures, which have been trapped within this icy storage facility for millions of years.

Ambers found in the Dominican Republic, which can be dated at 10 to 40 million years old, contain perfectly preserved insects with symbiotic bacteria in their stomachs. Some of these bacteria that have been entombed in the amber for more than 10 million years have been successfully cultured. The fact that viable bacteria can be isolated from samples preserved for millions of years has changed the way many of us feel about the interplanetary transport of life. It is not so easy to discount it as it once was.

So, if we are to proceed to another celestial body in search of life, our definition of habitability must be different from what we would have relied on just a few years ago. We must consider that the physical and chemical conditions tolerant to life are broader than we once thought. We must examine the potential energy sources available (Jupiter's moon Europa, for example, has a huge tidal energy probably equal to its solar energy) and look carefully for life forms utilizing any such energy. We must be prepared for subtle, single-celled life that may not be obvious at first glance, and we should look in places where life might have been preserved in dormant form.

But what precisely will we look for when we go to another planet or when we are fortunate enough to bring samples back to Earth? This is the question of the day for the new astrobiology group, which currently consists of, besides myself, a physicist, a high-energy physicist, a physical chemist, an inorganic chemist, an organic chemist, and a geologist. As I noted earlier, we're looking for properties of life that are universal and measurable, and the two features that we feel are of some obvious value: structure and chemistry.

Structures, as mentioned above, are the standard fare of the paleontologist, and when the structures of life are already known, they serve us very well. But when we are hunting in a new spot, dependence on known structures has a number of

Realistically, Mars will have to be our next laboratory. We need to practice studying Mars and get good enough to convince ourselves that we can detect life in other places without bringing a sample back.

potential traps, including the fact that we might discard structures simply because they are unfamiliar. It will be important to remain open-minded about the types and sizes of structures found in samples from new sites.

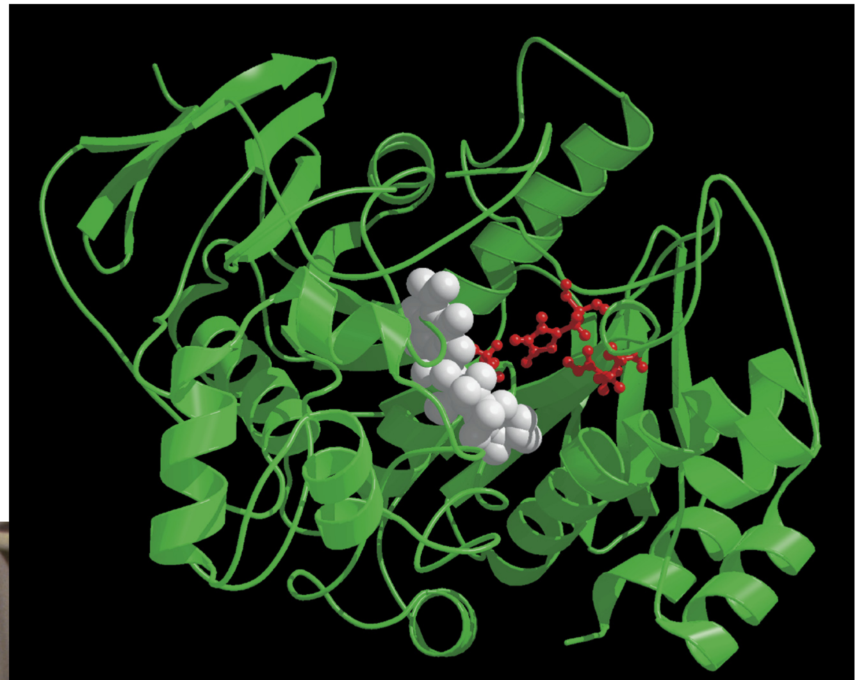
We cannot, however, rely simply on structural information alone. While we believe that life will be linked to some structural elements, these alone will not prove the existence of life. Coupling structural analysis with the determination of chemical content may well provide a tool for strongly inferring the presence of life. Life is, almost by definition, a source of negative entropy: a structure composed of groups of chemical monomers and polymers whose existence would not be predicted on thermodynamic grounds, given the abundance of chemicals in the atmosphere and crust of the planet. The exact nature of these chemicals is not so important as the fact that they are grossly out of equilibrium with their surrounding geological environment. If methods were available for analysis of the chemistry of structures at the proper size scales, then the possibility of detecting extant (or even extinct) life would be greatly increased. Ultimately, we would like to have samples from many places in our solar system and beyond, but Europa is a 10-year round-trip and a journey to Saturn's moon Titan and back would take 20 years. Realistically, Mars will have to be our next laboratory. We need to practice studying Mars and get good enough to convince ourselves that we can detect life in other places without bringing a sample back.

As our ability to measure structures and chemistry improves (and we have already developed the capacity for remote identification of elements by x-ray photoemission spectroscopy), the possibility of answering the question of whether life does or does not exist off Earth will improve as well. We will need a strategy for exploration, sample collection and return, and finally, sample analysis. Given the number of other solar systems already known to exist, and the emerging numbers of planets around far-away stars, it seems unlikely that life will *not* be found elsewhere. Development of the proper strategy, and definition of those conditions that do and do not support life will be key to the ultimate discovery of extraterrestrial life. With the proper strategy and approach, the question seems to be not one of whether there is life, but when we will find it.

The first Mars Sample Return mission is scheduled for launch in 2003. In the artist's rendering below, a rocket is fired from the Martian surface to put the sample into Mars orbit, where it will be retrieved and returned to Earth—and the eager hands of astrobiologists.

In 1998, Ken Nealson left what he describes as a cushy job as the Shaw Distinguished Professor of Biology at the University of Wisconsin to pioneer the new field of astrobiology at Caltech's Jet Propulsion Laboratory. He's a senior research scientist there, as well as a faculty associate in geology and planetary sciences at Caltech. Nealson earned his BS in biochemistry (1965) and PhD in microbiology (1969) from the University of Chicago. After 3 years at Harvard and 12 at the Scripps Institute of Oceanography, in 1985 he left for Wisconsin's Center for Great Lakes Studies. His work on extreme environments has taken him to lakes, fjords, and oceans all over the world, and when he first came to JPL in his new incarnation as an astrobiologist, he imagined himself some day swimming around on Jupiter's moon Europa—which turned out to require too long a time commitment. This article was adapted from a Watson lecture and a Seminar Day talk.

We jump a natural enzyme through a new hoop, and accumulate mutations that help it jump higher.



Unnatural Selection: Molecular Sex for Fun and Profit

by Frances H. Arnold

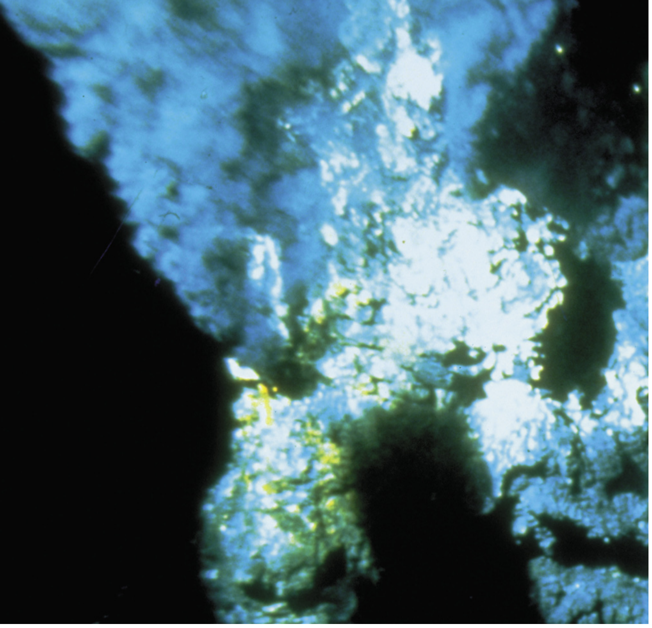
Top, left: Enzymes are molecular machines whose intricate shapes allow them to function. Here the protein backbone (green) cuddles the reacting molecule (gray) while holding a few amino acids (red) in just the right position to catalyze a reaction within the gray molecule.
Bottom: Proteins are really big molecules, but this is probably not the best way to modify them, as Mark Tomusiak (MS '91) and Ed Naranjo (BS '89) discover.

Proteins are nature's molecular machines. They're responsible for virtually all the interesting things that biological systems do. Enzymes, for example, are the ultimate chemists—they catalyze or direct all of life's reactions, and they're so remarkably specific that hundreds of reactions can proceed simultaneously inside a tiny cell. (One trillion *E. coli* bacteria will fit in a cubic centimeter.) This ability to synthesize complex materials at room temperature and pressure, in water, without waste products, rightfully earns enzymes the envy of synthetic chemists and the admiration of chemical engineers. One of the 21st century's challenges will be improving the world's standard of living without destroying our environment. That's going to be hard to do, but one way might be to recruit these highly efficient biological systems to work for us. My vision is of a biotechnology-based chemicals industry that makes no messes to clean up.

Now, the chemical engineer who actually has to implement this vision is constantly stymied by the fact that all these enzymes evolved over billions of years to perform very specific biological functions within the context of a living system. But the demands of industry are very different. You take an enzyme out of its natural context, and you find that many of its features are completely incompatible with cost-effective manufacturing. For example, imagine the chemical engineer's frustration with a catalyst that turns itself off the minute it produces a little bit of product. However, this control is vital to the cell, which carefully regulates its metabolism through such feedback loops. Industry wants enzymes that are highly stable (proteins don't take heat well—think of a hard-boiled egg), that can function in organic solvents (because many things we want to make aren't soluble in water), and that react with substances nature never even thought of. We'd even like to have molecules that perform reactions nature doesn't use. To do this we have to engineer enzymes at the molecular level—to redesign them for industrial use.

Unfortunately, we don't know how. Proteins are linear chains of amino acids (of which there are 20 natural varieties), and we understand pretty well the correspondence between the genetic code—the DNA sequence—and the protein that's produced. But what's not clear to us is how that chain of amino acids folds up into a three-dimensional structure. To a first approximation, if a given amino-acid sequence folds at all, it will always fold to the same shape, even in different environments. The folding information is somehow encoded in the amino acids. We would love to be able to predict how a given sequence will fold, but we cannot with any degree of reliability. And even more relevant—and much more complicated—is the question of how that three-dimensional structure and specific array of amino acids determines what that enzyme does—what reaction it catalyzes and how well it does it. We can't tell whether one enzyme is better than another in any of its properties just by looking at it.

Besides being the scaffolding that turns a few critical amino acids into a very precisely shaped pocket that catalyzes a specific reaction, an enzyme's structure and sequence also determine its sensitivity to heat and cold, its interactions with other molecules that turn it on or off, its stability in various solvents, and all its other properties. Making subtle changes in the scaffolding quite some distance away from the catalytic pocket in an attempt to engineer one of these other properties can alter the enzyme's reactivity. Sometimes this confers the ability to perform the same reaction on a new molecule, or to catalyze a different reaction; usually it just makes the enzyme sick, that is, less active, less stable, or both. Despite decades of intense research into these protein-structure-function questions, we're not even close to having enough information to design any given enzyme "rationally."

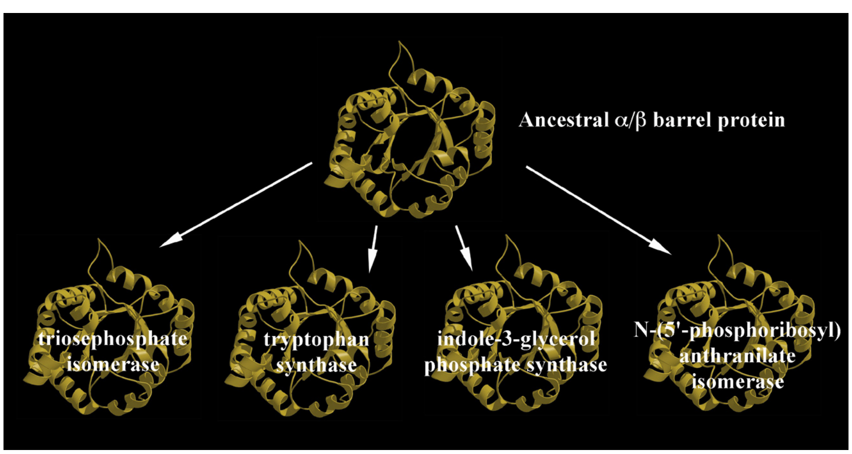


Left: A "black smoker," a type of geothermal vent on the ocean floor. This one is about a mile and a half deep. Long assumed to be barren, black smokers harbor entire food chains whose metabolisms are based on such things as hydrogen sulfide, ammonia, and methane. Photo by John Barrows, University of Washington, courtesy of Diversa Corporation.

To complicate matters more, the molecule is so flexible that the X-ray crystallographic data on which we depend for structural information often can't tell us what's really going on. Furthermore, enzymes are constantly teetering on the brink of conformational disaster. A large number of forces—hydrogen bonding, electrostatic interactions, interactions with solvent molecules, and what have you—stabilize the catalytically active three-dimensional structure. But an almost equally large army of forces is working to unravel it, including competing interactions with the solvent and the entropy cost of folding it up in the first place. The net energy holding the molecule in the folded, active position is perhaps the equivalent of only two or three hydrogen bonds, compared with the hundreds of hydrogen bonds in the folded protein. (For people who like numbers, this is a few kilocalories per mole, or about 8–17 kilojoules per mole.) This is a real problem for the protein engineer, because when you start monkeying with the structure it's easy to make it unravel altogether.

Now if the situation were really that grim, we could all just go home. Luckily, the protein-design problem is being solved all the time. As we speak, nature is creating proteins with novel functions in response to adaptive pressures. We can determine the amino-acid sequences of large numbers of modern proteins and, based on their degree of similarity, we can draw family trees that trace them back over hundreds of millions of years of divergent evolution. One ancestral protein can give rise to a huge family of proteins that look about the same but do many different things. Random mutation, recombination, and natural selection—evolution's "blind watchmaker"—have discovered fresh amino-acid sequences that confer new functions while conserving the overall three-dimensional structure.

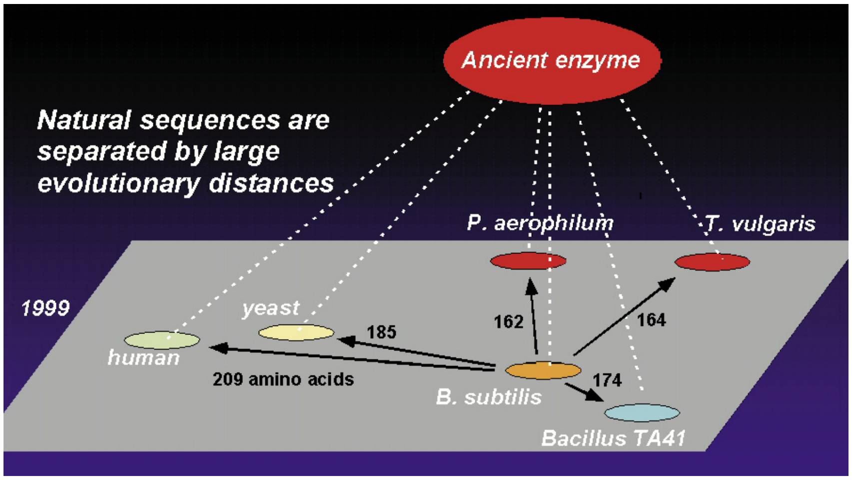
Below: Molecular evolution in action. Of all the enzymes whose structures are known, approximately 10 percent belong to the family of α/β barrel proteins, and presumably all evolved from a common ancestor. Although the progeny look alike to the casual observer, they do very different things.



Molecules can evolve a lot faster than you might appreciate. A phosphotriesterase has recently been found that degrades at diffusion-limited rates—as fast as a catalyst possibly can—pesticides and biological-warfare agents that were invented less than 50 years ago. It's quite possible that this enzyme has come into being in just the past few decades. On an even shorter time scale, as those of us who have children know all too well, all sorts of illness-causing bacteria are evolving drug resistance in response to the large amounts of antibiotics we throw at them. This is survival of the fittest at the molecular level—drug-defeating enzymatic changes allow the bacteria containing them to live long enough to reproduce. This is why it's so important to finish taking your medicine even if you feel better—you want to kill all the bacteria, not just the weak ones.

Molecular evolution also helps life occupy diverse environments. A volcanic feature called a solfatara is essentially boiling sulfuric acid—pH 0 and 95° C—yet it's home sweet home to the microorganisms that are just teeming there. And there's life under the sea ice around Antarctica at −1.7° C. Molecular evolution has given rise to enzymes that are perfectly happy under these extreme conditions. This makes engineers like me really envious, because these are some of the attributes we'd like our industrial enzymes to have. (For a closer look at some unlikely places where life thrives, see the article by Ken Nealson on page 30.)

You might think that comparing the sequence of, say, a heat-loving enzyme and a lower-temperature one that performs the same function would help us figure out what mutations to make, but life's not that simple. Above right is a slice through the bacterial family tree showing various relatives of subtilisin E, a protein-cleaving enzyme that works at body temperature. The corresponding enzyme from *T. vulgaris*, a bacterium that lives in volcanic vents, is different by 164 amino acids—59 percent of its sequence—and we have no idea which of those substitutions are really responsible for its high heat stability. Most substitutions are neutral mutations that neither help nor harm the organism. This is called genetic



Above: Subtilisin E, produced by *B. subtilis*, and its cousins produced by some other organisms. All of these enzymes break down proteins—in fact, subtilisin is widely used as a stain remover in laundry detergents. The numbers along the arrows indicate how many amino acids in each enzyme are different from subtilisin E.

drift, and it goes on all the time. Natural evolution is filled with historical accidents—random genetic drift—on which a little bit of adaptive evolution is superimposed.

We have discovered that the way out of the enzyme engineer's predicament is to look to nature—not for the specific molecules she has already made, but for the *process* she uses. Our challenge is to recreate, and direct, the evolution of molecules on time scales of less than hundreds of millions of years, because experiments of such duration really distress the grad students and are quite difficult to get funding for. For us, the maximum time unit for evolution is the PhD thesis—four years. But we'd really like to evolve new molecules in months or even weeks, which is now becoming possible.

Evolution may sound easy—just make mutations and see what happens. But that's not the case if you care about where you're going. Without a good strategy, your experiments are doomed to failure. That's because a typical protein has some 300 amino acids in its chain, and, with 20 letters in the amino-acid alphabet, there are 20^{300} ways to string those letters together. That's huge beyond imagination; huge beyond the number of protons in the universe. And this sequence space, if you will, is mostly empty—at least, mostly empty of the function you're interested in. So if you just wander around willy-nilly, it's not going to be a very useful exercise. For that reason, we do what nature does—we carry out local explorations of the space around existing, functioning molecules. We jump a natural enzyme through a new hoop, and accumulate mutations that help it jump higher.

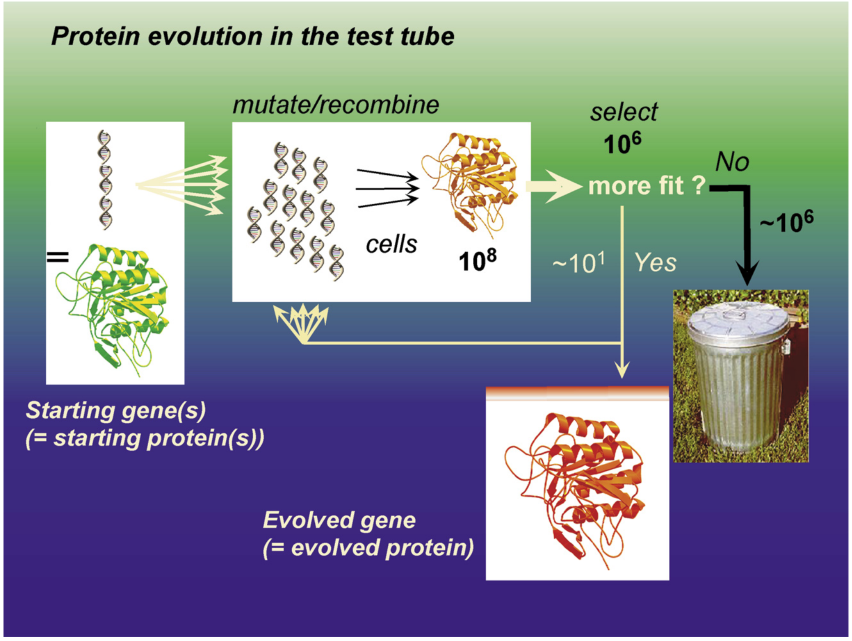
Just how local should this exploration be? If you plot, in the space of all its possible sequences, an enzyme's ability to perform a certain function (ignoring the fact that there are far too many dimensions to do this literally), the natural enzymes would be fog-shrouded mountain peaks, with the ground sloping away from them in (almost) all directions. If you take baby steps into the fog, however, you might discover that the peak is really a shoulder, and that the ground shortly begins to rise in one direction. But if you take a running leap, you're most likely to fall into a bottomless chasm. We find that the paths you discover taking small steps can often take you higher, sometimes much higher.

We have three major considerations in developing this experimental strategy. One is the first law of directed evolution: you get what you screen for. In other words, your success depends on how well your screen measures what you really want. The properties that you can measure easily may not be all of the ones that are important for the use you have in mind, so you either have to figure out some way of deducing the properties you're interested in from the properties you can measure, or you have to invest the time it takes to develop a new measurement(s). If you scrimp on this step, you'll wind up getting stuff you don't want. If you ask an evolutionary system to solve a problem for which trivial solutions exist, you'll get them, because they're easier to find. And if you just screen for one property (for example, the one you can easily measure), you may get a useless enzyme because it won't do the other things it's supposed to do.

The second consideration is that ways to improve a given enzyme are few, because enzymes are already so finely tuned. You could call this Murphy's law of evolution: most paths lead downhill. Even if you're asking the enzyme to do something completely new, most of the ways you can mutate it will make it worse. Beneficial mutations are rare, and combinations of beneficial mutations are extremely rare. So in order to find them, you have to do a pretty exhaustive search of your chosen area.

The third is that we have to screen enzymes by individually testing each mutant, one by one, to see how well it performs the combination of jobs that we're looking for. Given current technology, if we're clever and have a well-designed screen, we can maybe look at a million varieties of a particular enzyme per generation. This may seem like

Random mutation, recombination, and natural selection—evolution's "blind watchmaker"—have discovered fresh amino-acid sequences that confer new functions while conserving the overall three-dimensional structure.



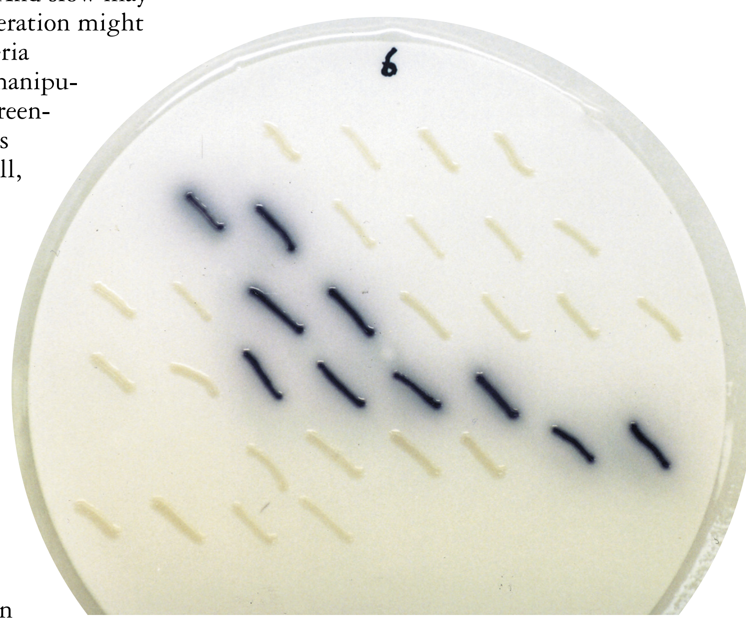
Above: Protein evolution by the numbers. Right: Colonies of bacteria on a petri dish. All the bacteria in any one colony are genetically identical to each other. The ones with the enzyme that performs the reaction we want have changed color.

a large number, but it's very small compared to sequence space.

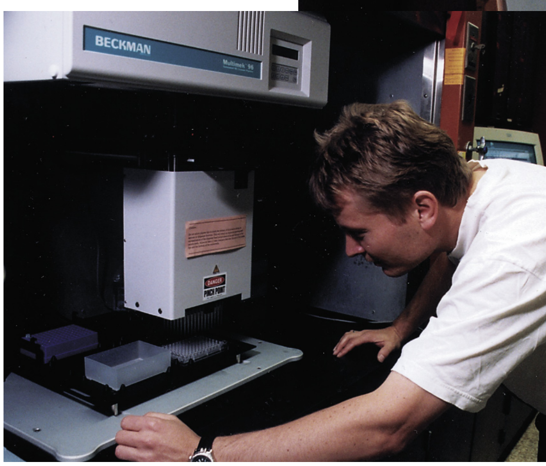
Together these considerations force us into the conservative, baby-step strategy—randomly changing only one or two amino acids at a time. There are 5,700 ways to change just one amino acid in a 300-amino-acid protein, 16 million ways to change two amino acids, and more than 30 billion to change three. The numbers grow so fast that it's impossible to search a reasonable fraction of even three-mutation sequence space, so instead we take a random walk of one- or two-mutation steps. This sounds slow, and pretty uninteresting, but what makes it all worthwhile is that mutations can be accumulated, either over many generations or, as I'll explain shortly, by recombination—a test-tube version of sex. And slow may not even be so bad, because one generation might take only a week or two. (The bacteria multiply overnight, but the DNA manipulation takes a day or two, and the screening takes the rest of the time. That's usually the bottleneck.) In a nutshell, we work with mutants that are very similar to their parents, and to do this we have to have a screening method that can measure small improvements in different functions simultaneously. Then we have to be able to accumulate these changes in order to make interesting, new enzymes.

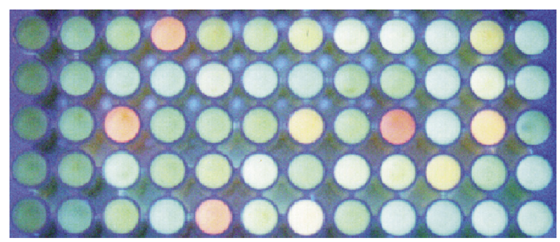
So how does the experiment actually work? First, we isolate the gene that codes for the enzyme of interest. Then we mutate that sequence of DNA in a test tube, using the polymerase chain reaction. PCR, as it's called, can copy a piece of DNA very, very fast. While we are doing this, we introduce mutations at a specific rate by forcing the copying catalyst (an enzyme!) to make mistakes. We get it a little bit drunk, if you will, by adding metal ions to the mix. So we get a bunch of sloppy copies and create a library, so to speak, of mutants. We insert each of these mutated genes back into a circular piece of double-stranded DNA, called a plasmid, which has all the information that a bacterium needs to translate the DNA into protein. Each plasmid with its different mutation(s) goes into one bacterium, so now we have several million bacteria, most with a slightly different gene than the one we started with. We pour them out on a petri dish (the bacteria are suspended in water and spread out on the nutrient-rich surface, so that each bacterium is physically separated from the others by dilution), where they grow and divide until you can actually see, with your naked eye, individual colonies of genetically identical bacteria—in other words, colonies of clones. You use a robot, or you hire a bunch of undergraduates who sit there with toothpicks, to transfer each colony into its own well on the assay plate. Even better, you measure the enzyme activity right there on the plate by adding a reagent that changes color or fluoresces when the reaction occurs and then taking a picture. Then you screen to find the mutant that's most improved, extract its DNA, and start the process all over again. You stop when you have the desired enzyme (or when it's time for the student to graduate).

What I've just described is evolution by random point mutation, but there are other ways, too. We like to spice things up by adding a little sex, for example. There must be some evolutionary advantage to sex, to make up for its obvious

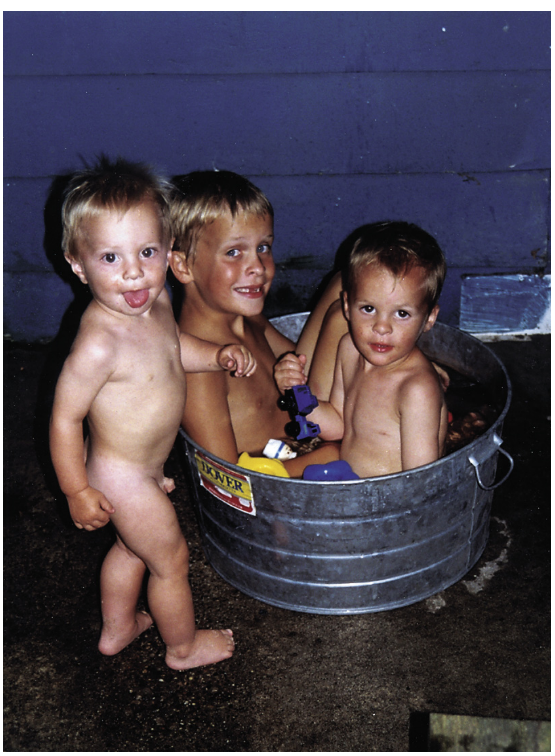


There must be some evolutionary advantage to sex, to make up for its obvious disadvantages. How else can you account for half the population not contributing to bearing the next generation?





Top right: Grad student Lianhong Sun uses an eight-channel pipetter to add reagents to a 96-well assay plate. Right: Or you can do the same job faster with a robot, as postdoc Oliver May demonstrates. Far right: Either way, you hope to get a reaction. Here, different variants of one enzyme are making different products from the same starting material.

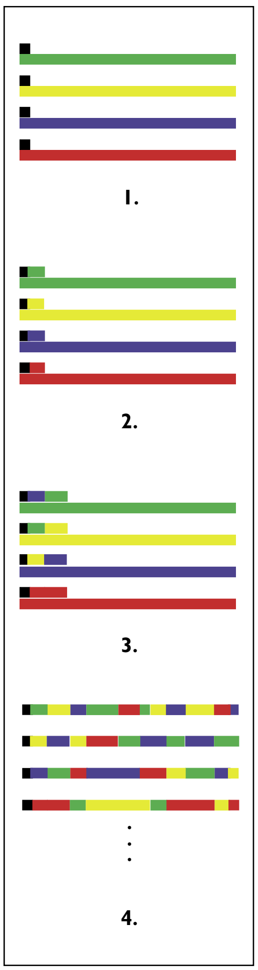


Left: The author's own products of evolution by recombination demonstrate their folding ability. From left to right are Joe (then one year old), James (eight), and Willy (two).

disadvantages. How else can you account for half the population not contributing to bearing the next generation? There are even things, like the peacock's tail, that are potentially harmful to an individual's survival. The compensation is that sex allows you to accumulate beneficial mutations from two parents at once, while flushing out the bad mutations. Molecular sex can be with any number of parents—sex with 50 even, if you can get all the genes to talk to each other. Sex is recombination, chopping up the genes and putting them back together in all possible combinations, so that now we're exploring a much larger (but still quite limited) region of sequence space. We can get the long legs and the thick hair from different parents, keep those good traits for the next generation, and throw out the undesirable offspring. Of course, it's much easier to do this with molecules.

How do you have sex in a test tube? Pim Stemmer, now at Maxygen, the company he

Below: Test-tube sex made simple. 1. Add a primer (black boxes) to several different versions of a gene (colored bars). 2. PCR begins copying the gene, starting at the primer. 3. When the primers come off and reattach, odds are they'll be on different genes than the ones they started on. 4. The result is a library of randomly shuffled genes.



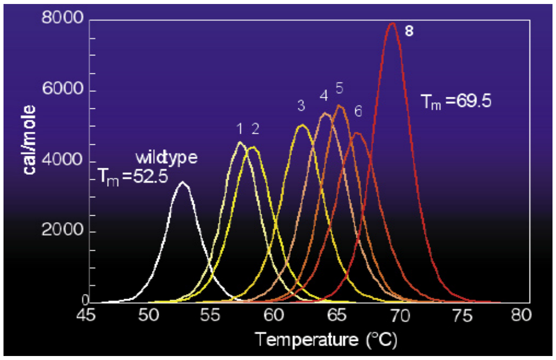
founded in Redwood City, invented this nifty method of gene shuffling that Huimin Zhao (PhD '98), postdocs Zhixin Shao and Lori Giver, my collaborator Joseph Affholter (who was at Dow Chemical but has since joined Maxygen), and I have improved. It's shown schematically at left. We put all the parental genes in a test tube and add a so-called primer, which is a short piece of DNA that initiates the PCR. The primer binds to a gene, and the PCR adds to the primer to make a copy. Normally, you'd let things run their course and get many complete copies. Instead, we heat the test tube after there's been time to process only, say, 20 letters or so, causing the primer and its unfinished copy to fall off the gene. When we cool the test tube back down, the primer latches on to the next parent gene it finds, and the PCR picks up where it left off. So if the primer was on the green gene initially, and landed on the yellow one in the second cycle, the copy will start with green information and continue with yellow information. And who knows—the next cycle might be blue. All this takes just a few minutes, and we end up with a library of what we call chimeric genes that contain randomly combined genetic information from the parents. (A chimera, in Greek mythology, had a lion's head, a goat's body, and a serpent's tail.)

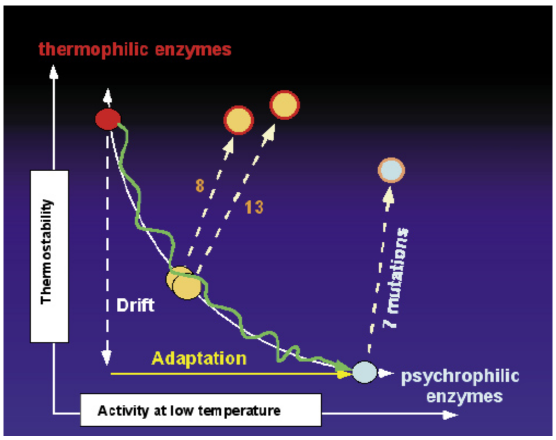
The next step is to find those rare good mutations and recombinations in your library. How you do this obviously depends on what you're looking for. I'll use an example of a thermophilic, or heat-loving, enzyme that we evolved. The enzyme is called para-nitrobenzyl esterase, because it breaks down the ester linkage in a family of compounds useful to synthetic organic chemists. We used a very simple screen on a 96-well plate (some plates have hundreds or even thousands of wells) to measure activity and thermostability at the same time. We made two copies of each master plate, and measured the initial activity on one copy after adding an ester that changes color when the enzyme cleaves it and seeing how fast the reaction proceeded. We roasted the second copy at a temperature high enough to cause the original enzyme to unfold, and then did the activity test on that plate. The mutants that passed became the parents of the next generation. Through a method called differential scanning calorimetry, in which we gradually heated the enzyme, we tracked how high we'd pushed the unfolding temperature. When a protein unfolds, it suddenly releases heat, so we measured the heat spike and noted the temperature.

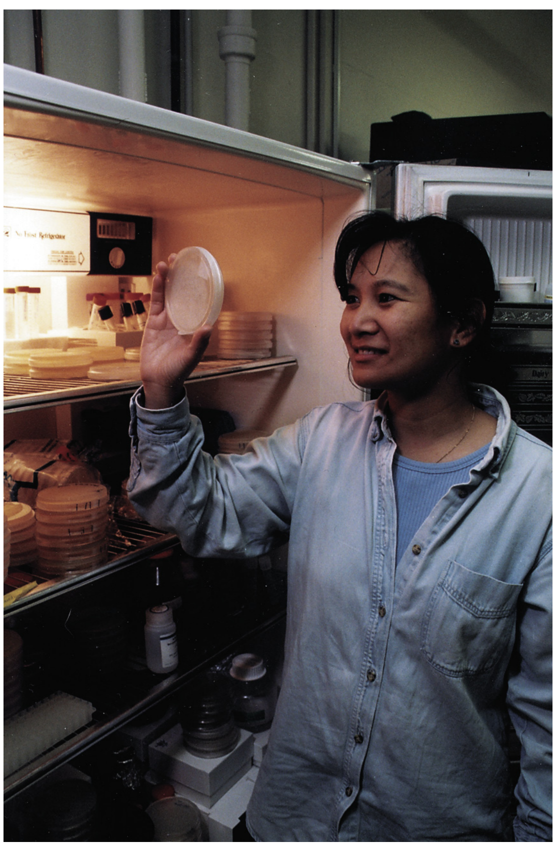
Postdocs Lori Giver, Anne Gershenson, and Per Ola Freskgard did five generations of asexual point mutations and ended up with five parents that were the starting point for some test-tube sex, followed by a couple more generations of point mutations. The final result was an enzyme that didn't unfold until the temperature hit 69.5° C (an improvement of more than 17° and fully equivalent to a naturally "thermophilic" enzyme). But remember, you get what you screen for. Stability is relatively easy to improve, but it almost always comes at a price—usually in catalytic activity. Our screen allowed us to look for evolving enzymes that at least retained the low-temperature activity of the original one. But the activity of the evolved enzyme increases as you raise the temperature, so that it is actually more than 10 times as active at high temperatures than the original enzyme is at its preferred (lower) temperature. Consequently, we evolved better activity hand in hand with thermal stability. This is the sort of thing that gets industry really excited.

Natural enzymes are usually optimized for the temperatures at which their organisms grow—the heat-loving enzymes don't work well at room temperature, and the room-temperature enzymes aren't stable when you heat them. So people have assumed that thermal stability and low-temperature activity are incompatible. They've even devised theories to explain it: a high-temperature

Right: Differential scanning calorimetry results for the evolved para-nitrobenzyl esterase. The original enzyme (white curve) unfolded at 52.5° C, but after eight generations of evolution in the lab, the unfolding temperature had climbed to 69.5° C.







Top, left: Assuming that life began at high temperatures, a psychrophilic (cold-loving) enzyme could have evolved from a thermophilic (heat-loving) one as shown by the green arrow. There would have been no incentive to preserve thermal stability, so it would have slowly drifted away. But with the proper choice of selection pressures, or screens, enzymes that are both thermostable and very active at low temperatures can be evolved with surprisingly few mutations (numbered arrows).

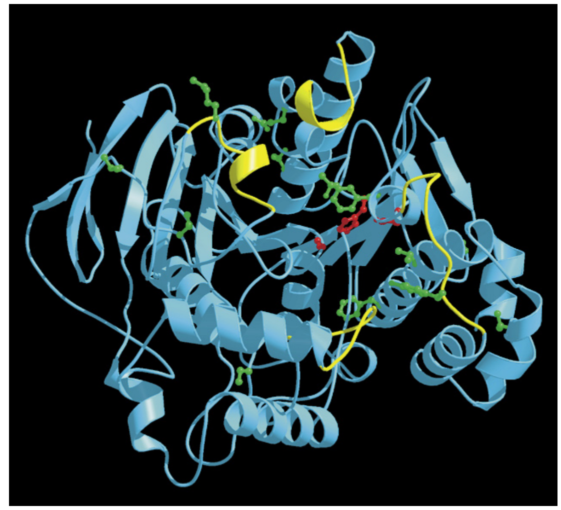
Left: Unlike the crud growing in most dorm fridges, this stuff is all being saved on purpose. Postdoc Anna Marie Aguinaldo takes stock.

enzyme has to be more rigid, so it will hold its shape, but a low-temperature enzyme has to be more flexible in order to guide the reactants when there's less energy available to the system. But here's another possible explanation: nature doesn't give a hoot about this combination of traits. Heat-dwelling organisms don't need activity at low temperature, and Antarctic bacteria certainly don't need heat resistance, so why go to the bother of making enzymes with both? If life began at high temperatures, as many scientists now believe, thermal stability may have been lost as enzymes more active at low temperatures evolved—because thermal stability wasn't needed any more, it drifted away. In the laboratory we can shed these biological constraints and really explore the difference between what's biologically possible and what's physically possible. We've found, to our delight, that a number of different properties are evolvable independently, which allows us to make very useful enzymes.

In the course of all this engineering, we can also study how a function evolves. During an experiment, we save all the intermediate mutants in the fridge. Once we've been successful, we go back and sequence the genes and identify the mutations that gave rise to the desired function. Here we found that only 13 amino-acid substitutions created this heat-loving para-nitrobenzyl esterase. We're not confounded by the hundreds of changes due to random genetic drift that would happen in a naturally evolving protein. In the laboratory, almost all evolution is adaptive, so we know that those 13 amino-acid substitutions are really responsible for the changing function. Knowing this, we can try to coax out the molecular mechanisms by which that property came about.

This is easier said than done. In fact, evolving a new enzyme is much easier than trying to figure out how it happened. Sometimes we ask for professional help. Professor Ray Stevens and his graduate student Ben Spiller at UC Berkeley

The evolved para-nitrobenzyl esterase (far right) and the original enzyme (right) look very much alike. The dotted lines are informed guesses—those portions of the enzyme were invisible to X-ray crystallography, presumably because their shape kept changing.

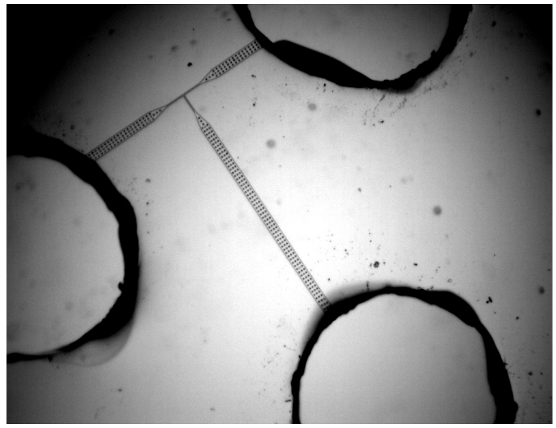


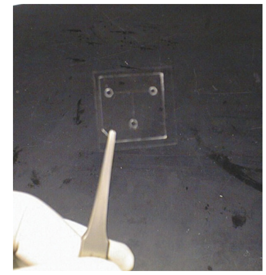
determined the three-dimensional structures of our evolved para-nitrobenzyl esterase and its progenitor. The structures are shown above. The red amino acids are the catalytic ones in the pocket where the ester binds. The sites of the 13 amino-acid substitutions are shown in green. It's fascinating to see how this enzyme has adapted. At first glance it might seem that nothing much has happened—the evolved enzyme folds up in pretty much the same way as its less stable and less active ancestor. But closer inspection reveals a number of interesting changes. What were two floppy loops (the dotted yellow lines in the ancestor's structure) have become fixed in the evolved enzyme. Mutations outside these loops in an early generation caused them to become rigid and added 11 new hydrogen bonds. This region then became a platform for further mutation later on. Two other loops (the solid yellow lines in the ancestor's structure) that control access to the catalytic site have also changed structure in the evolved enzyme. Note that most of these mutations are some distance away from the catalytic site. It would have been extremely difficult to predict them in advance. While we can rationalize the effects of each mutation after the fact, unfortunately there are no rules or patterns of substitutions that we could use in a future rational-design process. Kind of like "Buy low, sell high," the rules we generate are obviously true, but difficult to implement.

You can tune virtually any property of an enzyme to make it more useful for biotechnology, or to try to understand how the enzyme works. Laboratories around the world now are doing this with enzymes used in everything from laundry detergents to cleaning up chemical pollution. But if you want to create something really different, maybe even something totally new, nature doesn't offer much guidance as to how to go about it. Making an enzyme do something completely new is kind of like the species problem: it's easy to see how incremental changes create new breeds, but how do you make a whole new species when you can't imagine what a common ancestor—a transitional form that would get you from one species to the other—would look like? The problem is that it will probably take numerous amino-acid changes, and many at the same time, to convert one enzyme into another. But once again, sex offers a possible solution. The usual definition of a species is whether it can only have sex with its own kind, but we don't have such narrow-minded limitations in the laboratory. Molecules can have sex with anybody they want—sex with monkeys and worms and slime molds, if they feel like it. There only has to be enough similarity in the DNA for the gene-shuffling reactions to work. It might sound funny, but there's actually good reason to combine genes from widely divergent species.

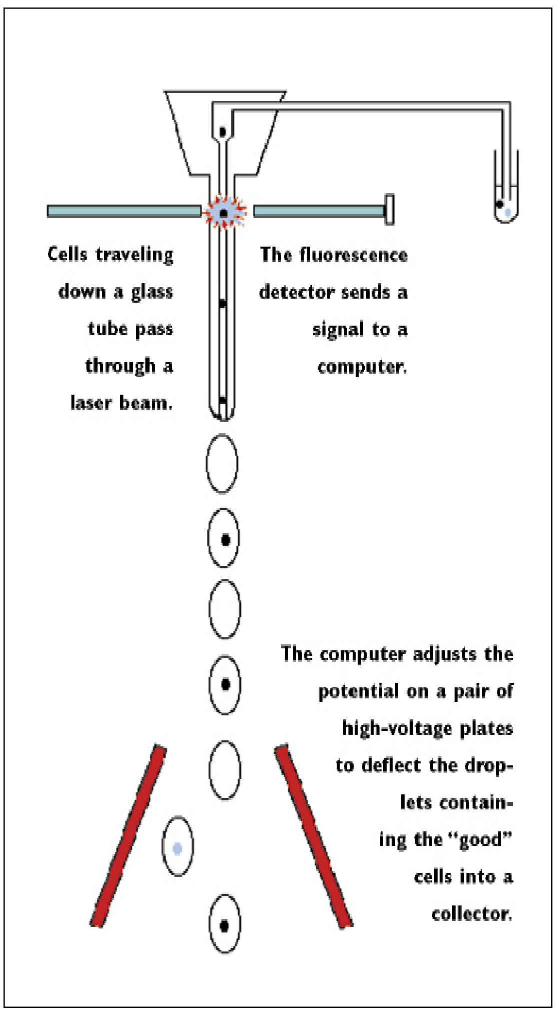
We have an enormous capacity now, through genome-sequencing studies and improved methods of gathering DNA in the wild, to identify genes for homologous proteins that have a variety of detailed differences in their sequences and functions. (Homologous means that the proteins come from a common ancestor and have essentially the same shape, even though their properties, or even functions, may have changed.) Pim Stemmer and his group at Maxygen showed that we can take homologous genes from various species and shuffle those genes to create a library of chimeras of enormous diversity, a fairly large fraction of which code for proteins that will still fold into the three-dimensional structure. (Remember, the hard part about making very large numbers of mutations is getting something that folds up properly in the first place.) But now that basic framework will be decorated with very different amino acids. These proteins can show a wide variation in properties, and possibly even completely new functions. (However, you do have to begin the process with some function in mind, in order to screen for

Right: A microphotograph of the T-shaped cell sorter. The black circles are the reservoirs for the junk cells, the keepers, and unsorted cells. The dots in the bottoms of the channels are pillars that hold up the roof.





Below: A conventional FACS uses electrostatic forces to sort cells (black blobs) as they fall from a glass dropper.

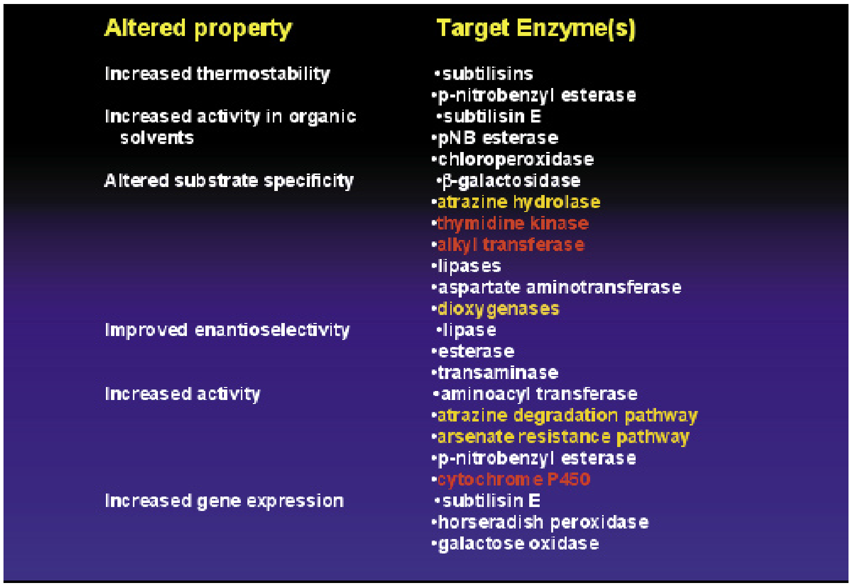


it.) So now, rather than exhaustively searching a little bit of sequence space close to the original enzyme, we're doing a sparse search in a vast but very special part of sequence space corresponding to folded proteins of the same overall structure. To return to the alpine analogy for a moment, we can leap from peak to peak like mountain goats. Of course, not all the peaks will be higher ones.

Moving on to even grander schemes, some day we'd like to be able to evolve whole new metabolic pathways—from a few to perhaps dozens of enzymes working in concert. To do so, we'll need to be able to look at enormous numbers of molecules, many more than we can look at today. We want to be able to evaluate 10^9 molecules, not just 10^6. Assistant Professor of Chemistry Rich Roberts has developed techniques he thinks will be able to look at 10^{13}. This is probably close to the upper limit for all practical purposes, just based on the mass of the molecules. It would get prohibitively expensive to work with much larger quantities of DNA.

In the meantime, our lab has been working with Associate Professor of Applied Physics Steve Quake's research group to develop a microdevice that can sort individual bacterial cells on the fly, based on their ability to carry out a reaction. The sorter is basically three wells and a covered, T-shaped channel, five microns wide and four microns deep (a bacterium is about one micron in diameter, and a micron is a millionth of a meter), cast in transparent silicone rubber from a silicon-wafer mold. The whole thing is about a centimeter square and fits on a microscope slide. The bacteria become fluorescent as a consequence of the reaction occurring. They enter at the base of the T, and as they flow, one by one, through a microscope's field of view, a computer reads the fluorescence signal and sends the cell into the T's left arm (the waste channel) or right arm (the collection channel) by changing the voltages at the channels' ends. This potential difference controls how the ions in the solution migrate, and the bacterium gets swept along in the current. Grad students Anne Fu and Charles Spence have built a prototype, shown above.

Conventional FACS (Fluorescence-Activated Cell Sorters) cost around $150,000, and they're terrible for working with bacteria. For one thing, they are very easily contaminated and take hours to clean out. Our plastic devices would cost a few cents and be disposable—you'd buy them in sterile pouches, like Band-Aids, use them once, and throw them away. Conventional FACS are also usually built to sort much larger cells from higher organisms like yeasts, plants, and animals, and have a hard time seeing bacteria. Our system will also be able to see the fluorescent bacteria much more easily. And conventional FACS imprison each cell in its own water droplet, which falls through a set of deflectors, so that you only get one pass through the sorter, while our microdevice is completely enclosed and lies flat. Steve's lab plans to exploit this by developing sorting



Above: Some of the enzymes that have been altered by directed evolution to date. The enzymes shown in yellow are designed for cleaning up various kinds of pollution problems, while the ones in red are intended to suppress unpleasant side effects of cancer therapy.

As *E&S* went to press, a paper written by postdocs Hyun Joo and Zhanglin Lin and me appeared in the June 17 issue of *Nature*. The paper describes the evolution of a cytochrome P450 that is much simpler than the natural enzyme. Cytochrome P450 is of interest to chemists because it inserts oxygen atoms into a huge number of compounds, but it's complex and ill-behaved. It needs a retinue of helper proteins and molecules called cofactors in order to work, and these guys are either impossible or very expensive to reproduce outside a cell. However, our P450 doesn't need any such help.

It's been known that hydrogen peroxide allows P450 to work unaided, so we turned this biochemical oddity into the enzyme's primary reaction pathway. Our version only took two generations to evolve and is 20 times better than the original one, which came from *Pseudomonas putida*, a soil-dwelling bacterium that uses it as a "digestive aid" to eat camphor.

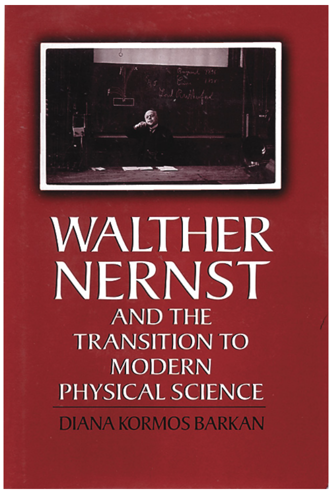
strategies that run faster than the switching speed. For example, we can run the machine really fast while shunting everything into the waste channel, and then when the rare good mutation zips by, we can quickly shift into reverse and draw it back out into the collection channel. It's like fast-forwarding through the commercials on your VCR and overshooting the point when the show comes back on—you just rewind a bit and catch it on the second pass.

The future of laboratory evolution is very bright, even though the field is only a few years old. Evolution is becoming a hot ticket because it works really, really well to solve problems that people care about. In fact, lots of labs in industry and academia are doing it. In a way, directing evolution is really a very old idea—animal and plant breeders have been doing it for thousands of years, albeit at much slower rates. Even with plants, you can generally only raise two generations a year, and you can only use two parents at a time. It's much nicer working with an organism whose population doubles every 20 minutes, and a gene that can have any number of parents. But it's a different way of thinking for many engineers and scientists, who aren't used to doing millions of experiments in hopes of finding one that works. Our knowledge is puny compared to what would be required to design enzymes from first principles, but if we settle back and admit our ignorance, it really frees us up to take this very different approach. These molecules are going to evade our understanding for quite a while yet. But when we use evolution, the lovely thing is that out come molecular solutions that *are* outside our understanding. So the future is no longer limited by our ignorance, it's really only limited by our imaginations. □

Ivan Claeys (MS '88, PhD '91) gets his start cleaning up in biotech.

Frances Arnold's career has traversed engineering and science in a seemingly random walk. She earned a BS in mechanical and aerospace engineering from Princeton in 1979, and a PhD in chemical engineering from UC Berkeley in 1985. She was a postdoc in chemistry at Berkeley and Caltech before joining the Caltech faculty in 1987, where she is now a professor of chemical engineering and biochemistry. Along the way, she has received the Office of Naval Research's Young Investigator Award, the National Science Foundation's Presidential Young Investigator Award, and a David and Lucile Packard Fellowship. Her research interests include designing strategies for in vitro evolution, developing high-throughput screening technologies for catalysts, and evolving interesting new enzymes (http://www.che. caltech.edu/groups/fha)*. She particularly enjoys raising her own three products of evolution by recombination.*

This article is a chimera created primarily from a SURF (Summer Undergraduate Research Fellowship) seminar given last summer and a recent Watson lecture.



Cambridge University Press, 1999
288 pages

Bombs, Diamonds, and Radium

by Alison Winter
Associate Professor of History

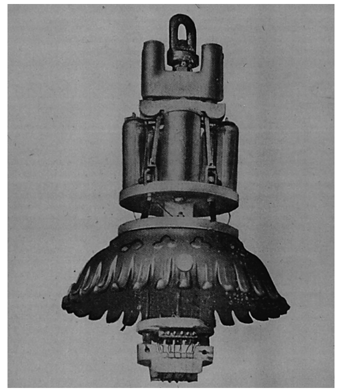
The curious tourist visiting imperial Berlin in the years before the outbreak of World War I might well have read in the newspaper of "strange things" happening at a quiet house near the center of the city. Situated close to the banks of the Spree, the premises housed a laboratory devoted to the new science of physical chemistry. It had been created in 1905 by the eminent scientist, academician, and privy councillor Hermann Walther Nernst. Here, the press revealed, Nernst and his colleagues were hard at work on a mysterious trinity of products that seemed to encapsulate all that was most exciting and most threatening in contemporary science: "bombs, diamonds, and radium."

In fact, the aim of Nernst's work was if anything even more momentous. He was developing the first-ever systematic program of experiments in low-temperature physics, with the purpose of understanding what he called the "heat death" of diamond. Nernst and his assistants succeeded in producing successively lower temperatures in their extraordinarily sensitive equipment, until they reached about –250° C. At this point there was a dramatic change in the diamond's character: no longer could heat be extracted from it. It was, as Nernst said, "frozen," to the extent that "the concept of heat does not exist any longer for the dead body."

Reducing a substance as symbolically revered as diamond to scientific extinction was a feat that could be expected to capture a reader's imagination. But its implications extended beyond poetry. Nernst's efforts were but one stage in an extraordinary career of invention, discovery, and innovation across a range of fields that seem, from the perspective of the modern disciplines of science, extraordinarily diverse—from industrial innovation to the most abstract propositions of theoretical physics. The three substances encountered that day in his Berlin laboratory symbolized Nernst's creativity in the realms of war, industrial wealth, and physical science: he did indeed contribute to the arsenal of the First World War, though in the form of poison gas rather than bombs; and his studies of thermodynamics took him from phenomena like that of the diamond's "heat death" to the vicissitudes of radiation. More lastingly, he played an instrumental role in the establishment of quantum theory in physics and chemistry. His work at the extremes of attainable temperature—high and low—culminated in his formulation of the "heat theorem," which would eventually be hailed as the third law of thermodynamics. By the time of his nomination for a Nobel Prize in 1921, Nernst would have presided over the emergence of central elements in the modern physical sciences.

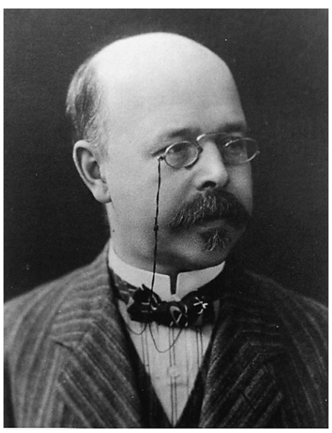
Nernst was a key figure in the development of the 20th-century sciences of physics, chemistry, and physical chemistry—indeed, the latter field was virtually his invention. It is therefore puzzling that until now no major discussion of his work has appeared. Diana Barkan's new book, *Walther Nernst and the Transition to Modern Physical Science*, more than compensates for this earlier deficit. Her monograph discusses and integrates every aspect of Nernst's various major enterprises, from the invention of an electric lighting device that almost preempted the modern bulb, to his work in electrochemistry, thermodynamics, and quantum theory. She even attends to the electric piano that he invented in the 1920s, which was transformed by Steinway into an early prototype for the electrically powered synthesizer. Each of Nernst's activities provides a context that helps give meaning to the others. One of Barkan's more provocative—and entirely persuasive—arguments is the idea that the development of the third law of thermodynamics, long treated as belonging to an abstract history of theoretical physics, must be understood as coeval with the industrial-technological

The heat theorem, Barkan shows conclusively, arose out of a combination of practical and theoretical efforts in problem-solving—efforts that treated disciplinary boundaries as almost entirely insubstantial.



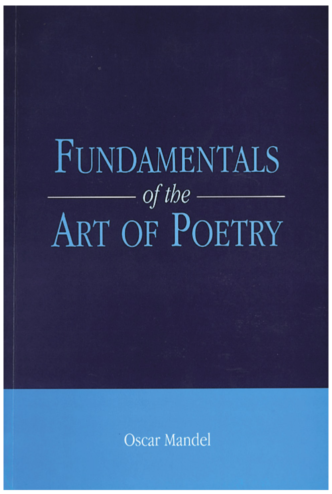
The Nernst lamp had burners of zirconium oxide, which conducted current when heated.

researches that Nernst was pursuing in the development of his electric lamp. Barkan, associate professor of history at Caltech, sensitively restores Nernst's efforts to their historical context, making clear what was at stake, and how he articulated and addressed the most important problems of his science.



One of the themes that runs through Barkan's study pertains to the history of scientific disciplines—the various territories of science, and the boundaries that are understood to lie between them. It has become customary as we look back at the early days of 20th-century science to see in it distinct endeavors corresponding to the professional disciplines that exist today. Nowadays, we have theorists and experimentalists, industrial scientists and academics; it is therefore natural that we tend to spot these divisions in the past. But in the case of a man like Nernst, Barkan makes it very clear that such divisions were by no means constant, and may not have existed at all. One more portentous consequence of Barkan's work is to show that we have systematically misconstrued the origins of scientific claims that are as fundamental as the third law. The heat theorem, Barkan shows conclusively, arose out of a combination of practical and theoretical efforts in problem-solving—efforts that treated disciplinary boundaries as almost entirely insubstantial. Nernst's work with electric lamps was as essential to his thermodynamics as was his work with hydrogen liquifiers, and a source of particular pride to Nernst himself (he fell out with his old friend Svante Arrhenius when he insisted on demonstrating the Nernst lamp in an elite Stockholm hotel, only to blow every fuse in the building). Science, then, is a kind of work that can only be understood if we are prepared to look beyond the formal statements that scientists make about their methods and results, to scrutinize the day-to-day practice of research.

Barkan convincingly demonstrates that Nernst played a pivotal role in the creation of modern physical science. The modern field of physical chemistry exists largely thanks to his career. Her central question is, "How are individual and group identities formed?" Her answer is that they are formed through individual and collective work of the kind that she documents in her study. Perhaps Nernst's greatest contribution to quantum theory, in particular, was to organize the first Solvay Conference on Physics, which met in Brussels in 1911. The conference itself achieved little and solved nothing—but its very existence proved to be a turning point. Nernst was in on the creation of a new form of scientific sociability. Manifested in the international congress, this sociability has underpinned the successes of science ever since. And it has also underpinned the emergence of what we would now say was Nernst's science—physical chemistry. Its identity was fixed publicly by Nernst's elevation to the Nobel laureateship, over the private opposition of Arrhenius. Arrhenius scorned his diplomatic efforts as mere "political flattery," but in 1921 his opposition was unique. And here lies a moral for today. We need to understand the work involved in establishing a technical scientific discipline like physical chemistry, because the boundaries that delimit it, if they become impermeable, can gain the power to bind as well as liberate. Diana Barkan's pathbreaking book helps us to question not only how the divisions between the sciences have developed, but what their status should be today. □



Sheffield Academic Press, 1998

351 pages

How does art work? What is good writing? What can a great picture, piece of music, or poem do for us?

Counterflow of One

by John Sutherland
Visiting Professor of Literature

For 38 years Professor of Literature Oscar Mandel has been exercising his civilising influence on Caltech undergraduates. During that period some 5,000-or-so students must have encountered in his classes what George Ellery Hale (as quoted in the *Caltech Catalog*) calls "the highest qualities of imagination"—without which, as Caltech's founding father nobly insists, no great work in science can be done.

Unusual when he was appointed in 1961 as associate professor of English (under the formidable Renaissance scholar Hallett Smith) Mandel is, as the century ends, the rarest of birds in literary studies. The words that best describe him, once terms of praise, are now deeply pejorative: "amateur" (in the sense of "lover of literature"), "dilettante," "belletrist," "connoisseur," "wit." Fluent in any number of European languages, Mandel has translated Marivaux, Corneille, and Kotzebue; imitated Calderón; commented on Sophocles and Thackeray. He has written monographs on the obscure (in both senses) Renaissance artist Magnasco and on Dutch vernacular painters for whose Flemish glumness he has, as a Belgian by birth, a peculiar fondness.

In an age of specialization, where scholars sit tight in their ring-fenced "fields," Mandel's free-ranging sensibility looks increasingly eccentric. Were he a younger scholar, embarking on his career, it would be downright suicidal to skit about as he loves to do. Not that it has ever bothered him being marginal. In his delightful collection of essays, *The Book of Elaborations*, he pictures himself as a graduate student at Ohio State in the 1950s as "the one and only inhabitant of Columbus, who on football afternoons walked *against* the joyous hordes on their way to the game, a counterflow of one."

Above all, Mandel is a practitioner. His writings about (as opposed to "in") literature have always been founded on the belief that—as T. S. Eliot put it—the only criticism that matters is that which explains the critic's own creative writing. Ask Mandel what matters most to him, and he will reply simply "my writing," by which he means, probably, the play, prose fantasia, essay, or poem he is currently working on. The poetry, in particular, is marked by a self-deprecation that is sly, charming and wholly characteristic of the man. His best known lyric is "Who's Diphilus?". (Who was he? A Greek whose verse has entirely vanished, leaving only a name, some anecdotes, and a reputation for being a half-decent poet.)

Who's Diphilus? His works are lost.
He was a poet, won
some prizes, dented time
in Greece among the better men,

And got thrown out one time because
he wrote a stupid comedy.
Ten scholars now remember him;
that too is immortality.

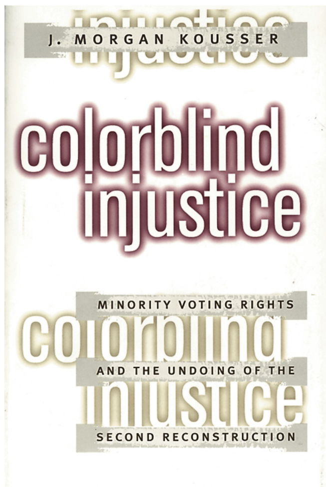
The plays are grander, indulging Mandel's Gallic love of high gesture and heroic rhetoric. In another of his many guises, he is the creator of wise and witty fables (see *The Gobble-Up Stories*). The flyleaf of this latest work lists no less than 23 books in 5 genres. Who's Mandel?

Over the last few years, as he has surveyed the drift in his subject toward specialization and theory (as it is misleadingly called), Mandel has become increasingly convinced of the need to return to what he conceives to be the basics of his discipline—"the rescue operation," as he calls it. How does art work? What is good writing? What can a great picture, piece of music, or poem do for us? To this end he has taken charge of the music, fine-art, and creative writing classes in the Division of the Humanities and Social Sciences, creating what is, effectively, a foundation course—*Kultur* 101. They are, one deduces from the packed classrooms, popular with students.

This latest book, as the title indicates, is part of the same general project. In one aspect it is what Ezra Pound would call an "ABC of Reading." Mandel himself calls *Fundamentals of the Art of Poetry* "an enchiridion—a guide book—for lay readers of any age." The tone of the book is marked by a kind of humane dogmatism. "What is Art?" his first chapter portentously asks. His answer, for someone so steeped in the grandeurs of European culture, is surprisingly materialistic, Brechtian almost. Art he conceives as primarily satisfying cerebral appetites. What this means is discussed in his second chapter, "Three Brain Centers"—a section of the book which suggests that some influential ideas have drifted across the Court of Man (can we still call it that?—Court of Person?) from biological Beckman to humanistic Baxter.

The body of the book is a "naming of parts" manual—a kind of aesthetic Auto-Ed. The approach is summed up in the breezy titles to chapters 9 and 10: "Practical Pointers for Reading Poetry"; "More Practical Pointers for Reading Poetry." Practicality goes with the realization that, at the end of the day, poetry will always elude the reader's grasp, however many pointers are supplied. "If you despair of elucidating all the allusions of a text," Mandel advises, "console yourself with the thought that we do not yet completely elucidate much of anything in this vale of tears, yet manage to live and enjoy life in that penumbra."

Enjoyment breathes over and through this volume. In one of its many parts, it is a judiciously composed anthology of the verse that has given Mandel most pleasure over the years—pleasure that he is adept in passing on to the reader and, one suspects, his Caltech students. May he have 5,000 more. □



The University of North Carolina Press, 1999

590 pages

History Matters

by R. Michael Alvarez
Associate Professor of Political Science

Race relations in America have long posed an enigma for social scientists, historians, and other commentators, in part because the problem has been such a shifting target. While routinely thought of in the context of the political and economic integration of African Americans, the question of race has also at various times and places concerned Asian Americans (especially in California since the Gold Rush) and other nonwhite immigrant groups, as well as Native Americans, Irish Americans, and Eastern Europeans. The analytic focus of social scientists and historians has changed dramatically in recent decades, however, as studies have become centered largely on how attitudes, beliefs, cultures, and customs shape race relations in America.

In his new book Morgan Kousser, professor of history and social science at Caltech, changes that focus to how *institutions* have shaped race relations in America.

Kousser's focus on institutions in the context of race relations is quite revolutionary. In recent years, a significant intellectual trend, termed the "new institutionalism," has swept through many of the social sciences, and Caltech's social scientists have been among the leaders of this approach. By "institu-

Not a mere observer of the historical events he describes in his new book, Morgan Kousser has actively participated in the judicial processes whereof he speaks. As he explains in his introduction, descriptions of the cases emerge directly or indirectly from his own experience as an expert witness in federal district court cases concerning minority voting rights—always on the side of minorities. Law, political science, and history all have their place in *Colorblind Injustice*, but Kousser considers it primarily a book of history. An understanding of the history of voting-rights policy, he believes, should lead to better public policy in the arena of race relations, an arena that Kousser has made his life's work.

History defines the Fourteenth Amendment. Its provisions do not mention race, ethnicity, gender, or religion, or single out any particular social group or governmental policy for special emphasis. A visitor from another country who knew nothing of American history could not discern from its words that the equal protection clause was particularly concerned with *racial* discrimination. If told that that clause banned the deliberate placing of significant numbers of some particular group into an electoral district, the visitor would have no less reason to believe, from the plain meaning of the text or from any abstract philosophical notion of equality, that the prohibited classication was of blue-collar workers or city dwellers or farmers or suburbanites or Democrats than that it was of African-Americans or Latinos. Only the history and continuing reality of racial discrimination and the connection of that discrimination with the adoption and development of the equal protection clause make racial differentiations especially relevant to it. Therefore, any gloss on that clause contains an implicit or explicit interpretation of the history of race relations in the country, and, conversely, every substantial difference in the interpretation of the history of race relations has implications for the understanding of the clause. Philosophy offers no guide to the Fourteenth Amendment or, rather, too many. For the equal protection clause, history, and only history, matters. Unless we get the history right, we cannot get the equal protection clause right.

from *Colorblind Injustice*, Chapter 9

tions" Kousser means laws and rules—those contained in the United States Constitution, in state and local laws regulating elections, and in the decisions of judicial bodies regarding political and electoral laws. *Colorblind Injustice: Minority Voting Rights and the Undoing of the Second Reconstruction* is a sweeping study of how these institutions shape race relations in both productive and unproductive ways.

In Chapter 5, "A Century of Electoral Discrimination in North Carolina," Kousser offers particularly telling examples of some of this process. He poses a strong challenge to the redistricting arguments that were made in the early 1990s in North Carolina. That state, which from 1898 through 1992 had not elected a single African American representative to the U.S. Congress, produced a districting plan that carved out two oddly shaped majority African American districts. Unsurprisingly, these two districts elected African Americans to the U.S. House of Representatives in 1992.

But almost immediately after taking effect, this plan was challenged in court in the *Shaw v. Reno* (1993) and *Shaw v. Hunt* (1996) cases, and the Supreme Court overturned the redistricting. Kousser argues that one of the intriguing ironies was the repeated assertions by the political actors in court that "No court or agency has determined that racial discrimination has ever occurred in the creation of congressional districts in North Carolina" (page 243). Kousser nonetheless demonstrates that, just as the newly drawn 1992 congressional districts improved racial balance by electing African American congressmen, similar racial gerrymandering in the post–Civil War era packed African Americans into a single congressional district to *reduce* their ability to achieve widespread political representation.

The rest of this massive study contains numerous other examples of how institutions have changed the shape of society—racial discrimination in the establishment of electoral laws in Memphis (Chapter 3) and Georgia (Chapter 4), and race and redistricting in Los Angeles (Chapter 2) and Texas (Chapter 6). In each of these chapters, Kousser eloquently recounts the historical detail of each example and thoroughly marshals overwhelming quantitative support for his arguments.

Kousser's extensive use of quantitative data in his historical analysis strengthens his arguments; it also provides a significant and interesting counterweight to recent trends in research. Unfortunately, in my opinion, traditional historical research has come under strong attack in recent years from the same postmodern and linguistic fads that have swept through the humanities, especially literature. These trends have infected historical research in many areas, including the history of race relations. By shifting the analytical focus away from interpretations of facts and data, these postmodern historical studies have sharply reduced the impact of historical studies in academic research and in current political debates about issues such as affirmative action, bilingual education, and immigration reform.

Colorblind Injustice constitutes a powerful statement to historians, demonstrating that quantitative and factual historical research is not a methodology that should be abandoned in the face of postmodern attacks. Instead, the book is a call to arms for historians—exactly the type of well-documented, well-argued, and strongly quantitative historical study that can serve as a counterpoint to postmodern critiques of contemporary historical research.

Kousser has written an important book on the history of race relations in America, clearly documenting the progress made in developing a more politically egalitarian society. *Colorblind Injustice* is also significant for its analytic focus on how institutions shape that society. Given the lessons learned by previous attempts to use laws, rules, and regulations to mitigate or enhance racial political equality, policy makers now have important information at their fingertips to use in devising institutional changes. And, finally, this book is imporant for Kousser's passionate offensive aimed at regaining the intellectual high ground for factually and quantitatively driven historical research. □

ELEANOR M. SEARLE
1926 – 1999

Medieval historian Eleanor Searle, the first woman appointed to a named professorship at Caltech, died April 6. She was 72.

She had been named the Edie and Lew Wasserman Professor of History in 1988, after joining the faculty as professor of history in 1979. Searle grew up in Chicago, where she attended the Latin Girls' School. Her undergraduate years were spent at Radcliffe College, from which she graduated magna cum laude in 1948. Initially interested in the law at a time when women were not routinely admitted to law school, Searle changed direction and headed for the Middle Ages. Although denied law school, she did become the first woman to study at the Pontifical Institute of Mediaeval Studies in Toronto, where she received her LMS (Licentia Mediaevorum Studiorum) degree, magna cum laude, in 1961 and her DMS (Doctor Mediaevorum Studiorum) in 1972.

During a visit to Pasadena in 1959, where her astronomer husband, Leonard, was doing research at Caltech, Searle discovered the Huntington Library and its Battle Abbey papers. Her research on his superb collection of medieval records from 1066 (the abbey was built on the site of the Battle of Hastings) to 1538 was the basis for three of her books. She had remained a senior research associate at the Huntington ever since.

Searle also taught at Caltech as a lecturer in 1962–63. After five years at the Australian National University in Canberra, the Searles returned to Southern California, where Leonard joined the staff of the Mt. Wilson and Palomar Observatories (he was named director of the Carnegie Observatories in 1989). Eleanor was appointed associate professor of history at UCLA in 1969 and promoted to professor in 1972.

In her scholarly work, she had a remarkable range of interests, said Scott Waugh, professor of history and dean of social sciences at UCLA—from old Normandy to 15th-century England, from kinship to monasticism. "But her real interest, the thread that ran through all her work," said Waugh, "was power and how power was exercised, both in the small context of Battle Abbey and the larger context of England as a whole. She was interested in the bases of power: inheritance and land, and family and kinship. But always in the background of her work were the questions: Who profited? What institutions benefited?"

An interest in women's property rights led to her most recent book, *Predatory Kinship: The Creation of Norman Power 840–1066*, which was published in 1988. She was, said her colleague Philip Hoffman, professor of history and social science, "one of the best medieval historians in the world. Her books are very well known among medieval scholars," and her last one accessible and enjoyable to nonspecialists as well.

Searle was a fellow of the Medieval Academy of America, and served as its president in 1985-86. She was also a Fellow of the Royal Historical Society and of the Society of Antiquaries of London, and was honorary vice president of the Battle and District Historical Society. At Caltech she was vice chair of the faculty in 1985 and executive officer for the humanities from 1989 to 1992. She retired with emeritus status in 1993.

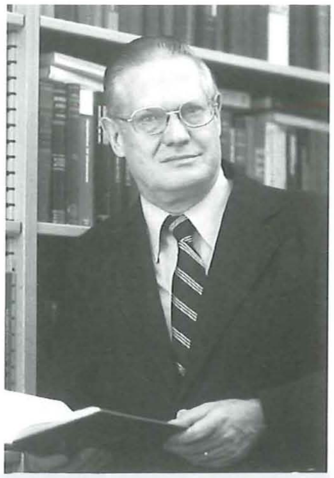
Peter Fay, professor of history, emeritus, described her as "a splendid teacher," whose courses always drew significant numbers of students. Fay, who had known Searle in the early '60s, remembers her as "possibly the best lecturer that I'd ever heard anywhere then—just remarkable." Waugh, who knew Searle first when he was an undergraduate at UCLA and then as a colleague, portrayed her as "full of curiosity, energy, and enthusiasm, which she transmitted to her students. Her students would get swept up in whatever she was engaged in."

Friends remember her as a voracious reader, a devoted traveler, lively, charming, with great wit and "fantastic spirit." She was "a very gracious, witty, accomplished woman, and a supportive colleague," said Annette Smith, professor of literature, emeritus.

In 1989 Searle led a group of The Associates on a trip to Normandy (and then across the English Channel to replay the Battle of Hastings), which earned her splendid reviews. "She knew a *great* deal about Norman history and was fun to be with," recalled J. Howard Marshall III '57, PhD '65. Carl Larson '52 remembered her "contagious enthusiasm and sense of humor, which made it fun for all of us."

A memorial service for Eleanor Searle will be held on November 4. □

Carl Larson presents the flag of the Norman dukes to Eleanor Searle during The Associates' trip to Normandy in September 1989.



Donald E. Hudson 1916 – 1999

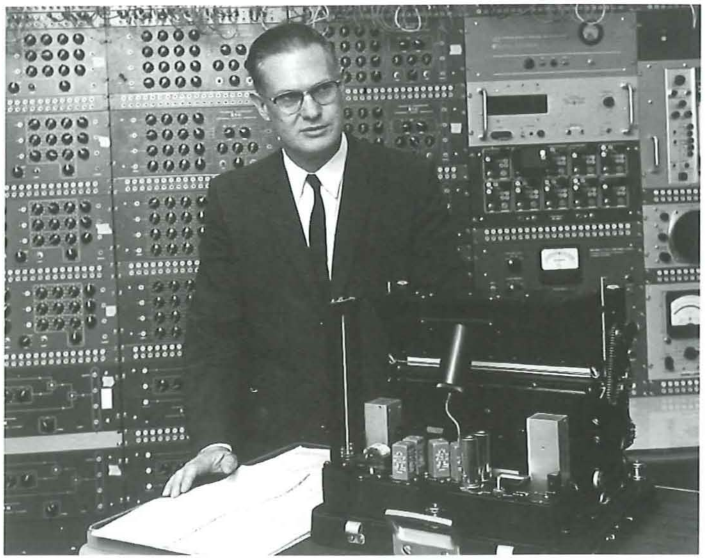
Donald Hudson, professor of mechanical engineering and applied mechanics, emeritus, died April 25 at the age of 83. A pioneer in the field of earthquake engineering, Hudson developed or codeveloped a number of instruments used in the study and analysis of seismic motions for designing quake-resistant buildings, bridges, and dams.

Hudson was almost a native Pasadenan. Born in Michigan, he moved here at the age of eight, attended Pasadena schools, graduated from Pasadena High School, and attended Pasadena City College. In 1936 he transferred to Caltech, where he earned his BS in 1938 and began his long career at the Institute. After finishing his PhD in 1942, he joined the faculty as assistant professor in 1943. He was named full professor in 1955 and served on the faculty until he retired with emeritus status in 1981. Then he traveled down the freeway to the University of Southern California, where he chaired the School of Civil Engineering and held the Fred Champion Professorship in Civil Engineering until retiring a second time in 1985.

Other professional activities outside Caltech included a stay at the University of Roorkee in India in 1958-59, where he set up the postgraduate program in earthquake engineering, still one of the best in the world; and a tour of Central and South America with UNESCO to improve earthquake safety. During World War II, he worked on aircraft torpedoes for the Navy.

His research over the years included dynamic measurements in the field of vibrations and experimental stress analysis, general analysis in structural dynamics and vibrations, and analytical and experimental methods in earthquake engineering and engineering seismology. He was instrumental in developing the first multi-unit building vibration generator with precise frequency controls. He also headed the project of analyzing all strong-motion accelerograms—digitizing the data, computing velocity, displacement, and response spectra and publishing the results in a multivolume set of books in the 1970s. The coauthor, with George Housner, of two important textbooks—*Applied Mechanics-Statics* and *Applied Mechanics-Dynamics*—Hudson also published more than a hundred technical papers and reports.

Elected to membership in the National Academy of Engineering in 1973, he was also a member of the Seismological Society of America (president 1971-72), the American Geophysical Union, and the Indian Society of Earthquake Technology. He was a fellow of the American Society of Mechanical Engineers and the Indian National Academy of Engineering, and an honorary member of the Earthquake Engineering Research Institute and the International Association for Earthquake Engineering, which he served



Don Hudson helped design a number of instruments for analyzing earthquake. He is shown here in 1966 with his analog spectrum analyzer.

as president from 1980 to 1984.

In 1989, the American Society of Civil Engineers awarded its Nathan M. Newmark Medal to Hudson for his contributions to structural mechanics and measurement analysis and his interpretation of the response of structures to dynamic forces and motions. He was also awarded the Housner Medal in 1992 by the Earthquake Engineering Research Institute.

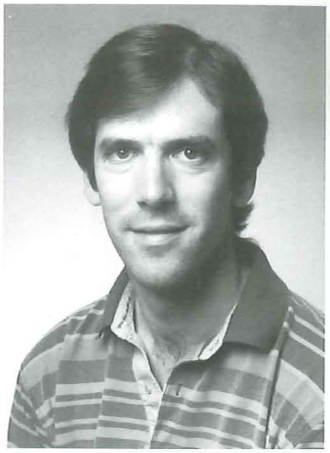
Several of his longtime colleagues, almost all of whom had known Hudson for 40 to 60 years, spoke at a memorial service in Dabney Lounge on June 17, recalling Hudson as a teacher, mentor, and colleague. A common theme in everyone's recollections was Hudson's calm and patience, his love of music, and his thoroughness and generosity. Paul Jennings, PhD '63, professor of civil engineering and applied mechanics, former provost, acting vice president for business and finance, and a former student of Hudson's, claimed to "still know exactly where my notes are [for Hudson's courses] in case I have to rely on them once again for courses that I teach." His blackboard work was so beautiful, said Tom Caughey, PhD '54, the Hayman Professor of Mechanical Engineering, Emeritus, "you could have photographed it and published it as a book."

Bill Iwan, '57, PhD '61, now professor of applied mechanics, spoke of how he "literally fell in love with dynamics" in Hudson and Housner's course. Hudson's enthusiasm in class also carried over into his lab work, Iwan said, and "taught me something about what *my* attitude ought to be toward research." Samri Masri, PhD '65, now professor of civil engineering at USC, praised Hudson's leadership at that institution, during what Masri described as "essentially an extended sabbatical from Caltech," where he was "a true father of future generations of earthquake engineering research." His many productive PhD students there are "proof that the legacy of his ideas will live and multiply through his students and his students' students."

In the earlier part of his career, Hudson was notably a member of a small group of inveterate bachelors on the Caltech campus—"the most confirmed bachelor I ever met," said Jennings. Caughey related how he remembered distinctly that when Earnest Watson finally married at the age of 62, George Housner, another bachelor, sternly warned Hudson to keep his guard up; "eternal vigilance is the price of freedom." But Hudson apparently let his guard down and in 1972 married Phyllis Patterson, "the first really great secretary we ever had," according to Harold Wayland, professor of engineering science, emeritus. The Hudsons enjoyed traveling together, something they did in their characteristic well-organized way, journeying around the world sharing one suitcase.

He read widely in history and literature, collected Asian art, loved music. Hudson, said Wayland, was the epitome of what Caltech's founders "were trying to achieve when they insisted that all undergraduate students put between 25 and 30 percent of their time in the humanities"—to become "human beings and not just engineering automatons." George Housner, the Braun Professor of Engineering, Emeritus, who had known Hudson since they shared a cubicle office as teaching assistants in 1939, described his love of art and music. "Don," said Housner, "spent a considerable fraction of his income on records, the old 78 rpms." When 33s came in, he started all over again amassing a new collection. And then came compact disks; Hudson started collecting those too. Although Hudson was fondest of string quartets and Lieder, said Housner, when once he happened to be exposed to a recording of the Beatles' "Sgt. Pepper's Lonely Hearts Club Band," he allowed that "there really is some musical merit in there."

Rolf Sabersky, professor of mechanical engineering, emeritus, who claimed that he and Hudson had seen each other almost every day for 50 years, ended his remarks by addressing Hudson "wherever you are—I'm sure there's a round table where the faculty meet for lunch. Reserve a few seats for us, as we will be joining you there and will continue where we left off." □



Andrea Goldsmith
Raymond Deshaies

New Business, Finance VP Named

William A. Jenkins has been appointed vice president for business and finance.

Jenkins has been vice chancellor for administration at Vanderbilt University since 1984 and has held an adjunct professorship of management in the Owen Graduate School of Management since 1988. As a general officer of the university, he is directly responsible for activities encompassing finance, business, technology, human resources, and facilities; he has also been involved in fundraising, academics, student life, athletics, and legal, community, and public relations. In 1990 he created the Vanderbilt University Leadership Development Forum, which provides leadership training for academic and administrative staff throughout the university.

Before joining Vanderbilt, Jenkins spent seven years at North Carolina State University as assistant and then associate vice chancellor for finance and business, and before that was business manager and assistant to the vice president for campus affairs at Cornell University.

Coauthor of the book, *The Eagle and the Monk: Seven Principles of Successful Change*, Jenkins is a recognized speaker, consultant, and authority on the subject of leadership and values. He is also coauthor of *Managing the Hidden Organization* and is author or coauthor of numerous articles in popular, higher-education, and business publications. Honored for his activities in the areas of race relations and the advancement of women, Jenkins is also a Purdue University Distinguished Alumnus. He earned his master's and PhD degrees from Purdue, and his bachelor's degree from Indiana State University.

Honors and Awards

Jacqueline Barton, the Arthur and Marian Hanisch Memorial Professor and professor of chemistry, has been elected a member of the American Philosophical Society "for her achievements in science."

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

Raymond Deshaies, assistant professor of biology, in July 1997 was awarded the 1997 Burroughs Wellcome New Investigator Award in the Basic Pharmacological Sciences.

Professor of Chemistry *Dennis Dougherty* and Professor of Economics and Social Sciences *John Ledyard*, who is also chair of the Division of the Humanities and Social Sciences, have been elected fellows of the American Academy of Arts and Sciences.

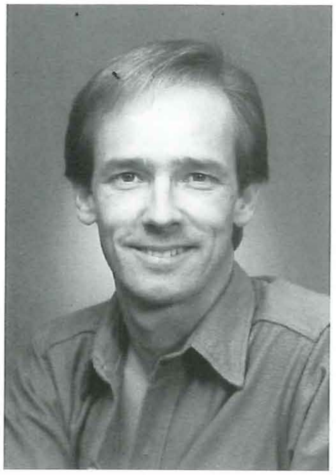
Peter Goldreich, the Lee A. DuBridge Professor of Astrophysics and Planetary Physics, has been selected by the department of astronomy at the University of Texas, Austin, to receive the Eighth Award of the Antoinette de Vaucouleurs Memorial Lectureship and Medal. "Known as one of the preeminent theoretical astrophysicists in the world," Goldreich is "especially acclaimed for the diverse areas to which he has made fundamental contributions. His work is both mathematically rigorous and resonant with deep physical insight." His many other honors include the National Medal of Science.

Andrea Goldsmith, assistant professor of electrical engineering, has been selected as an Office of Naval Research Young Investigator "for her exceptional promise for an outstanding research and teaching career."

Robert Grubbs, the Victor and Elizabeth Atkins Professor of Chemistry, has won the 1998 prize from Fluka Chemie AG, Switzerland, for his development of the reagent of the year, "a novel olefin metathesis catalyst based on a ruthenium carbene complex."

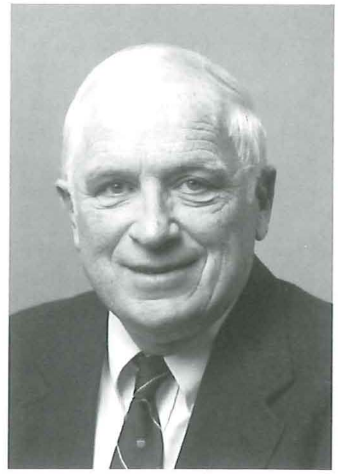
Bruce Hay, assistant professor of biology, in February 1998 was awarded the 1998 Burroughs Wellcome Fund New Investigator Award in the Biological Sciences.

Alice Huang, senior councilor for external relations and



Kerry Sieh

Anneila Sargent



James Morgan

faculty associate in biology, has received the 1999 Achievement Award from the Chinese-American Faculty Association of Southern California, for "her outstanding contribution" to microbiology and "her dedicated leadership in higher education." She was recognized at the association's 28th annual convention, where she gave the keynote speech, "New Challenges for Chinese-American Activism."

Emlyn Hughes, associate professor of physics, has received the Richard P. Feynman Prize for Excellence in Teaching "for his outstanding ability to teach the mysterious nature of quantum mechanics to a broad audience, as evidenced by the overwhelmingly positive student feedback from Ph 2, a core course in sophomore physics. By combining a clear pedagogic style with an entertaining delivery, complete with frequent anecdotes on physics and life, Hughes brings a Feynman-like quality to the teaching of this difficult subject." The prize consists of a cash award of $3,000 and is matched by an equivalent raise in the annual salary of the awardee; it is made possible by a gift of endowment from Caltech Associates Ione and Robert E. Paradise, "in appreciation of Richard Feynman's contributions to excellent teaching."

Hideo Mabuchi, PhD '98, assistant professor of physics, and *Rahul Pandharipande*, associate professor of mathematics, have both been selected to receive Alfred P. Sloan Research Fellowships. Each fellowship carries with it a grant of $35,000, to be used "in a flexible and largely unrestricted manner so as to provide the most constructive possible support" of the recipient's research. Sloan recipients are selected on an extraordinarily competitive basis from a group of nominees representing the very best of young scientists.

Carver Mead '56, PhD '60, the Gordon and Betty Moore Professor of Engineering and Applied Science, has been awarded the Lemelson-MIT Prize.

James Morgan, the Marvin L. Goldberger Professor of Environmental Engineering Science, has been named the cowinner (with Werner Stumm, professor emeritus of the Federal Institute of Technology in Zurich, Switzerland) of the $150,000 Stockholm Water Prize for 1999, awarded by the Stockholm International Water Institute for substantial contributions "to the preservation, enhancement or availability of the world's water resources." Morgan and Stumm "have for decades been the paramount scientists" in their field, and they coauthored the book *Aquatic Chemistry*. Morgan has also received the National Water Research Institute's 1999 Clarke Prize; the $50,000 award is given each year in the field of water research and technology. "Dr. Morgan's career contributions to the body of knowledge encompassing the many fields of water science and technology have been truly exemplary," according to the Clarke Prize citation.

Anneila Sargent, PhD '77, professor of astronomy and director of the Owens Valley Radio Observatory, has been elected president of the American Astronomical Society (AAS). Her term of office as president-elect begins this June, and she will serve as AAS president from June 2000 to June 2002.

Ronald Scott, the Dotty and Dick Hayman Professor of Engineering, Emeritus, has been selected to receive an Honorary Membership in the Earthquake Engineering Research Institute "for his very significant contributions to earthquake engineering."

Kerry Sieh, professor of geology, has been elected to the National Academy of Sciences.

Barry Simon, the IBM Professor of Mathematics and Theoretical Physics and executive officer for mathematics, has received the Technion—Israel Institute of Technology's highest honor, the Doctor Scientiarum Honoris Causa. The conferral took place on June 14. The honorary doctorate is in recognition of his contributions to mathematical physics in general as well as to a variety of specific fields involving quantum and spectral theory, his "influential and lucid textbooks," and his "promotion of scientific cooperation with Israel and the Technion." □

Debt Repaid, Many Times Over

Marcella and Clifford Burton

I developed an interest in science while attending Coffeyville Junior College in Kansas. My decision to attend Caltech was based largely on economics. My parents and I concluded that I could get my degree from Caltech for a lot less than it would cost me at, say, MIT.

It wasn't until I had earned my bachelor's degree in applied chemistry from Caltech in 1940 and had become active in the Alumni Association that I fully realized what a bargain my Caltech education had been. The $300 a year I paid in tuition didn't begin to cover the cost of educating me. A large proportion of the cost had come from contributions to Caltech by alumni and others. I decided that this was a debt I should attempt to repay when I was financially able.

My first significant move in this direction came in 1966, when I joined the Caltech Associates and eventually became a member of the President's Circle. My wife, Marcie, and I have very much enjoyed our activities with The Associates. We recommend it to others.

Before my retirement from C F Braun & Co. in 1982, I was fortunate in having selected as investment advisors some excellent stock pickers. They did a fine job, and with the help of the bull market, my wife and I found ourselves with a sizable portfolio of highly appreciated stocks.

That was wonderful, but there was a problem. The advisors' research indicated that some of these highly appreciated stocks should be sold. This produced a large capital gain and corresponding tax. My wife and I didn't mind paying tax on capital gains we intended to spend, but we did object to paying tax on money that we probably would end up giving to Caltech or some other charitable institution.

Our first attempt to remedy this situation was to invest in a series of Charitable Gift Annuities from Caltech. We were able to purchase these with highly appreciated stock without paying tax on the capital gain when the stock was sold. A portion of the stock's value is treated by the IRS as a donation, further reducing taxes. This was a move in the right direction, but it moved our investments out of the equities market and into the fixed income market. We didn't want to go all the way in this direction.

A Charitable Remainder Unitrust seemed to solve this second problem. Again, we could fund the trust with appreciated stock without incurring capital gains tax. And again, we got a substantial tax deduction for our donation. Caltech reinvests and diversifies the proceeds from the donated stock and pays us a fixed percentage of the Unitrust account value each year, as long as either of us is around. After that, the remainder of the trust goes to Caltech.

Marcie and I feel fortunate to have, in retirement, this kind of financial problem. We are pleased to have found a solution that is good for us, and that also benefits Caltech.

Cliff Burton '40
Distinguished Alumni Award '74

For information, contact:

Chris Yates, JD
Susan A. Walker, CFP
Office of Gift and Estate Planning
California Institute of Technology
Mail Code 105-40
Pasadena, California 91125
phone: (626) 395-2927
fax: (626) 683-9891
planned_gifts@caltech.edu
www.gep.caltech.edu

Engineering & Science

California Institute of Technology
Pasadena, California 91125

NON-PROFIT ORG.
U.S. POSTAGE
PAID
PASADENA, CA
PERMIT NO. 583