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IN THIS ISSUE

Ricketts arcade in the early morning light as seen by JPL mission designer Charley Kohlhase, who digitally removed years of stains and scuffs, coffee cups, and a bicycle, then added the auras of past students. *Caltech* hung for a year outside the office of JPL's director—the orderly interplay of architecture and lighting oftens appeals to both artists and scientists; for more on a life in both worlds, see the story beginning on page 18.

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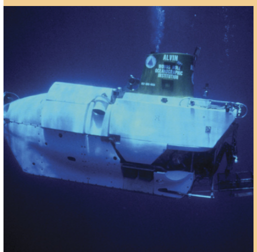

On the cover: At the Lucky Strike volcano, 1,700 meters below the Atlantic, chimneys aptly named black smokers pump out sooty seawater that's been to the bowels of the earth and back, while mussels nestle as close as they can without getting boiled. On page 8, Paul Asimow discusses why the rocks, hot water, and animals are so unusual here.

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Voyager at 25—Still Boldly Going

The Voyager mission marked its 25th anniversary this year—Voyager 2 launched on August 20, 1977, and Voyager 1 followed on September 5—and the twin spacecraft that opened up the outer worlds of our solar system to us are still going strong. Voyager 1, now the most distant human-made object from Earth, and Voyager 2, a close second on a different path, are on their way to becoming our first interstellar probes. They are now searching for the heliopause—the edge of the solar system, where the stream of charged particles from the sun meets the free-drifting ions of interstellar space. A commemorative exhibit of Voyager images is on line at http://beacon.jpl.nasa.gov/exhibits/voyager/default.html.

Broad Center Dedicated

The Broad Center's facade is clad in travertine marble and stainless steel. As Baltimore said, one is "redolent of the Beckman Institute and the historic buildings on campus; [the other,] clearly new and challenging, a harbinger of the future . . . reminds us that a new, scientific research building is an ambitious thrust into the unknown."

The Broad Center for the Biological Sciences was dedicated on September 10. Named for Caltech trustee and SunAmerica chairman Eli Broad and his wife, Edythe, the building will house 13 research groups. Representing a mix of disciplines, they will mount a joint attack on what Elliot Meyerowitz, chair of the biology division, called two of the great problems of biology: "How cells work—the ultimate in nanotechnology. And how the brain works—the most complicated problem in biology, and maybe the most complicated problem we'll ever face." Those problems may well be solved within Broad's walls in the next 20 years, he said.

Renowned architect James Freed of Pei Cobb Freed & Partners designed the building to foster communication. The labs are built on an open plan, and researchers with similar interests share the same floor. And immediately adjoining is a café where, in the words of Caltech president David Baltimore, generations of students, postdocs, staff, faculty, and the occasional administrator can discuss "science, the affairs of the world, or the latest tennis match."

The third and first floors will be the domain of the cell. Upstairs, biologists Pamela Bjorkman, David Chan, and Grant Jensen and chemist Douglas Rees will be studying the structure and function of assorted molecules, while downstairs biologist/chemist Stephen Mayo (PhD'87), mathematician Niles Pierce, and two future faculty members will be using computers to design proteins and other molecular machines.

The cell- and brain-research floors are interleaved for maximum idea exchange in the stairwells. On the second floor, biologists Erin Schuman and Kai Zinn will examine various aspects of how neurons connect and communicate; two labs are still to be occupied on this floor too. And biologist Scott Fraser will oversee the basement MRI facility, one of whose magnets is big enough to do brain-function studies on humans.

Eli Broad, whom Baltimore described as a "venture philanthropist," said, "We are often asked, 'Why did we make this cornerstone gift?'

Above: Eli Broad.
Below: As the only eatery on the west side of campus, the Café at Broad will bring together people from many disciplines, leading to who-knows-what collaborations.

It's because biotechnology, more than any other scientific discipline, has the potential to make the greatest possible contribution to human well-being this century.... [We] will place L.A. squarely in the forefront of the greatest growth sector of the 21st century." □—*DS*

A Freeway Runs Through It

The Arroyo Seco runs some 20 miles from the San Gabriel Mountains to the Los Angeles River. Spanish for "dry gulch," it's actually a good-sized canyon whose intermittent stream, permanent ponds, and fertile floodplain have been a sanctuary for wildlife and humans for at least 8,000 years. In the last 100, it has also become the chief conduit between downtown Los Angeles and Pasadena, containing, at various times, a wood-planked elevated bikeway, the Santa Fe railroad, the Arroyo Seco Parkway, the Pasadena Freeway, the Metro Rail Gold Line, and soon perhaps again a bicycle expressway. At the same time, its streambed from just south of JPL has been dammed and encased in concrete in response to the catastrophic floods of the 1910s, '20s, and '30s. And, of course, the Arroyo is home to the Rose Bowl, a golf course, swimming pools, tennis courts, hiking trails … It's in this context of balancing refuge and recreation, torrents of water and streams of cars, that Caltech, Occidental College, and UCLA last year jointly offered a course entitled, "Re-Envisioning the Arroyo Seco Corridor: Watershed, Transportation, Ecological, and Community Building Issues."

The lower Arroyo Seco was channelized in 1938 because of rainfalls like this. Norm Brooks (PhD '54), Irvine Professor of Environmental and Civil Engineering, Emeritus, took this shot looking downstream at the two-lane bridge that connects JPL with its east parking lot on March 4, 1978, at the end of what National Weather Service meteorologists rated a series of "moderate-intensity" storms during which the rain gauge on Mount Wilson recorded 24.16 inches of rain in six days. What looks like a dead tree wedged against the pier is really water being thrown two meters into the air, from which Brooks says a flow of about six meters per second can be calculated.

William Deverell, Caltech associate professor of history; Robert Gottlieb and Marcus Renner of Oxy's Urban and Environmental Policy Institute; and Richard Weinstein of the department of architecture and urban design and Anastasia Loukaitou-Sideris of the urban planning department, both at UCLA, taught the course in concurrent sessions on their home campuses. The class shared a reading list (which included *Eden by Design*, cowritten by Deverell and Greg Hise, associate professor of urban history at USC) and met jointly twice, but otherwise took a different focus at each institution. Oxy took on issues important to the surrounding communities. UCLA offered a graduate-level "studio" course that did things like redesign the Pasadena Freeway's abrupt transition to a surface street, using the Arroyo to create a gateway to the city of Pasadena. And Deverell's class explored the Arroyo's historical and cultural legacy.

Of the course's 45 students, three were Caltech undergrads. John Harris (BS '02), Derek Jackson, and Meghan Smith (BS '02) did fieldwork with Deverell as well as classwork, he says. "It was great to tap into the students' knowledge of geology, biology, and so on, and apply that to local history. And it was fun to spend time with the students off campus, out of context." Their destinations included the Huntington Library, where dining-room furniture belonging to Caltech trustee Henry Robinson (as in Robinson Lab) is part of an exhibit on the works of Charles and Henry Greene. Says Harris, "We were all very surprised to learn about all the ways that Caltech was related to Arroyo culture." For example, renowned tile maker Ernest Batchelder taught art at Throop Polytechnic, Caltech's forerunner, leaving in 1909 in protest over the school's increasingly theoretical bent. But he and his wife remained active in school affairs: the Coleman Chamber Concerts bear her name.

For those of you who aren't up on local history, it starts with the Tongva, rechristened the Gabrielinos by the Spanish—hunter-gatherers whose women wove beautiful, complex reed baskets, now highly prized, as well as huts large enough to shelter an entire extended family. The Arroyo was relatively unused by the Spanish ranchers and farmers, and many dispossessed Tongva still lived there when California joined the Union in 1850. Pasadena was founded in 1886, the year after the Santa Fe railroad arrived and just in time for the land boom that followed. "The Arroyo was a nationally acclaimed recreation area that drew and retained visitors from all over the country," says Harris. For

A group of city folk enjoy the Arroyo's tranquility in this undated photograph by one E. A. Smith of Pasadena, courtesy of Bill Deverell.

tubercular, asthmatic Easterners, it was a small conceptual leap from "warm, dry air is good for the lungs" to "living outdoors is good for you," and thus was born the Arroyo Culture, which would define Pasadena's, and indeed Los Angeles's, self-image until the 1920s—an idealized vision of the desert southwest, both Tongva and Hispanic, adapted for American life.

The Arroyo Culture applied the notion of "living in nature" to all aspects of existence—the California bungalow, with its spacious patios and sleeping porches, and the plein air (literally "open air") style of painting being just two of its manifestations. The Arroyo and its banks became populated with bohemians and artisans (including Batchelder) of all sorts—the Southern California incarnation of the Arts and Crafts movement that had sprouted in England. This urban wilderness became the archetype of a new, suburban lifestyle, says Deverell; not city, not country, but something in between. (Of course, this was a lot easier to achieve at the turn of the century, when the county's population was comfortably under a million.) Even so, not everyone could afford to live in a Craftsman house by Greene and Greene (or even a modest bungalow), and support grew for officially turning the Arroyo into a park so that the working classes, too, could experience nature.

In 1928, in a spirit of noblesse oblige, the Los Angeles Chamber of Commerce—the men who moved and shook the Southland in the days before plate tectonics—commissioned a report called *Parks, Playgrounds and Beaches for the Los Angeles Region*. Two years in the making by the Olmsted brothers and Harland Bartholomew, the leading landscape architects and city planners of the day, this comprehensive blueprint also included large wilderness reservations suitable for camping, hiking, and horseback riding. These were to be connected by parkways or "pleasureway parks," laid out so "that no home will be more than a few miles from some part of it; and … so designed that, having reached any part of it, one may drive within the system for pleasure, and *with* pleasure, for many miles.… [They] necessarily should be greatly elongated real *parks*." Landscaped to be screened from their surroundings, and "having few cross-traffic intersections," they would "produce, along with the topographic conditions, some sense of spaciousness and seclusion, and a variety of scenic effects." Yes, recreational driving was already an acknowledged pastime—by 1930, there were two automobiles for every three people in L.A., the highest per-capita ratio in the world, says *Eden by Design*.

The proposed Arroyo Seco Parkway ran from downtown Los Angeles to the San Gabriel Mountains, feeding into what is now the Angeles Crest Highway. But as studies by blue-ribbon commissions are wont to do, this one sank without a ripple. In the words of the Techers' project report, "Shamefully, the reasons this plan for a countywide parkway system failed were primarily political ones. The proposal would have required a new countywide agency with extensive powers to appropriate spending, but the Chamber of Commerce … did not want to share their power.… Business leaders were also opposed to the plan because they believed that it would take up too much valuable real estate.… Even during the Depression, hundreds and thousands of people were migrating to southern California from other parts of the country, making the real estate business extremely lucrative … 'city beautiful' ideas were pushed into the background."

Although much of the Arroyo's floor was eventually converted into a chain of parks, the result was neither the originally envisioned "pleasureway" nor a proper freeway, but something in between. Dedicated December 30, 1940, to coincide with the Tournament of Roses (the Rose Bowl had been built in 1926), the Arroyo Seco Parkway is the oldest limited-access highway west of the Mississippi. It's been designated an American Civil Engineering Landmark and is eligible for the National Register of Historic Places. It was laid out so that you could see magnificent vistas from behind the wheel, it followed the contours of the landscape, and it featured decorative walls and bridges, but it also had a large median and wide lanes for its day, and banked curves to keep the traffic humming at the state speed limit of 45 miles per hour. It was designed to

The Arroyo Seco today, with its flood-control channel and six-laned freeway. Designed in more leisurely days, this tiny off-ramp (note the 5 mph speed limit) dumps you unceremoniously into the surrounding neighborhood.

carry 27,000 cars per day, and now handles about six times that. Furthermore, says the Techers' report, "Most of the adjoining parkland goes unused, except by the local residents. Many acres of parkland have poor street access or have dilapidated facilities, and most of these parks are not even known to be open to the public."

So, what can be done at this late date to reconnect the freeway to the Arroyo Culture? If we can no longer "live in nature," can we at least drive in it? In March, the combined class presented their work to invited guests at the Los Angeles River Center and Gardens, at the confluence of the Arroyo and the Los Angeles River. Among the Techers' proposals was one to restore the original sight lines. Says Harris, "If a few 'shielding' trees were removed in a couple of places, views of the mountains could be much more dramatic." And, says the report, "all chain-link fences should be removed or obscured with something artistic and natural. These barriers and other roadside structures could be built with Arroyo stone or use aesthetic designs that are culturally significant to the Arroyo." Better signs and more historical markers would raise awareness of the surrounding parks, which need renovation, and a low-power radio transmitter like those that broadcast freeway closures could beam a program on Arroyo culture and history into your car.

It could happen, says Tim Brick, director of the Arroyo Seco Foundation, who was in the audience that day. The foundation released its own *Arroyo Seco Watershed Restoration Feasibility Study* in Caltech's Ramo Auditorium five months later, on August 21. "I was impressed by their recommendations, and we went back and beefed up parts of the watershed report from it," said Brick. "They really caught the spirit of the Arroyo." He continued, "Caltrans has recently obtained Federal Scenic Byway status for the Parkway, which means that a lot more attention will be paid to upgrading its 'look' and historical character." Meanwhile, according to UCLA's Loukaitou-Sideris, the Metropolitan Transit Authority and Caltrans are studying UCLA's proposed Arroyo-Walk, which "connects and highlights a number of cultural sites" accessible to pedestrians, while at the same time "proposes visual elements to enhance the motorists' views and perception of the area as a cohesive landscape." And Renner reports that Oxy's students have produced a brochure and Web site (http://students.oxy.edu/wheatley/bikeproject.htm) on expanding bicycle use in the Arroyo area, and another brochure listing its cultural resources. He's including them in an Arroyo educators' guide that will go out to 50 to 100 teachers of grades K–12 in October.

The joint syllabus for the course calls the degree of collaboration "unprecedented," and Renner concurs. "It was an experiment, and we learned how to do it better next time, which we'd like to do." Says Deverell, "It was a joint idea by all three campuses that just sort of grew out of discussions. I'd like to do it regularly—the mountains one year, the beaches the next, and so on. It's this kind of flexibility, and the resources of the Huntington Library, that makes teaching humanities here so rewarding." □—*DS*

TALK AMONG YOURSELVES

Jehoshua Bruck, the Moore Professor of Computation and Neural Systems and Electrical Engineering, has been named one of the collaborators in the Alpha Project, a $15.5 million, five-year program to explore how living cells respond to information and communicate with one another. Administered by the Molecular Sciences Institute and funded by the National Institutes of Health's National Human Genome Research Institute, the project will also involve research groups from MIT, UC Berkeley, and the Pacific Northwest National Laboratory. Bruck's specialty is distributed information systems—essentially groups of devices such as cell phones or laptops that interact over some kind of communication network. Here, he will help analyze cellular signal transduction, abstract its key features, and model them.

Signal transduction is a set of chemical interactions between genes, proteins, and signaling molecules that control how a cell communicates with other cells or senses things in its environment. The Alpha Project will focus exclusively on the pheromone signal pathway in baker's yeast, whose cells' signal-transduction system is quite similar to ours. The pheromone pathway involves a relatively small number of about 25 genes, so it is hoped that thoroughly understanding the system will provide new insights on human cells.

Bruck has already collaborated informally with the Molecular Sciences Institute to create computer algorithms for simulating more general biological regulatory systems. "We are not planning to conduct experiments with yeast in my lab," he says. "Our part will be to model the whole process, and create simulations to try to predict the behavior of the biological system. Also, we plan to learn from biology about new principles in circuits for computation and communications, because at present we simply don't know how to build artificial systems that compute, communicate, and evolve like biological cells."

Success for the overall project could lead to new ways of dealing with diseases such as cancer and diabetes. "At the least, we'll definitely understand this communication pathway in cells," Bruck says of the biological goals. "And if we are able to understand the mechanisms in a way that leads to advances in curing diseases, and this information can also be applied to engineering systems, it would be even better."

The Alpha Project will be the Molecular Sciences Institute's new Center for Genomic Experimentation and Computation's flagship project. The Molecular Sciences Institute, headquartered in Berkeley, is an independent, nonprofit research laboratory that combines genomic experimentation with computer modeling. The institute's mission is to predict the behavior of cells and organisms in response to defined genetic and environmental changes, which would significantly increase our understanding of biological systems and help catalyze radical changes in the practice of medicine. The institute can be found on the Web at www.molsci.org. ☐—*RT*

Radar Survey Unmasks Active Volcanoes

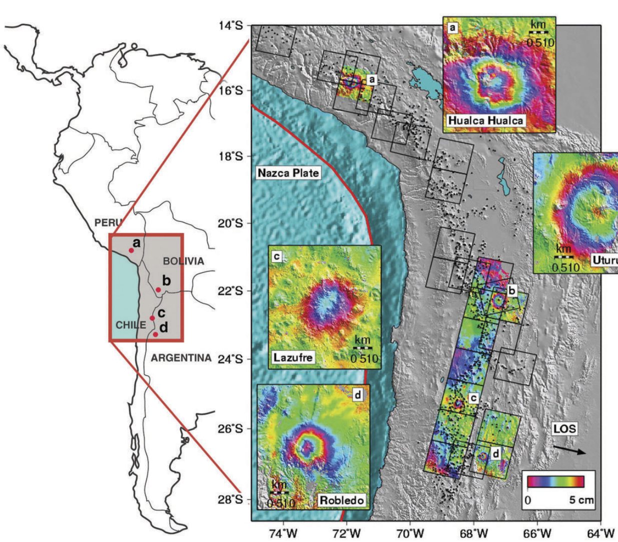
Four Andean volcanoes thought to be dormant have been revealed to be active by an innovative radar survey that tracks ground motions from space. Caltech grad student Matt Pritchard (MS '00) and Assistant Professor of Geophysics Mark Simons have analyzed interferometry data on 900 Andean volcanoes—data gathered from 1992 to 2000 by the European Space Agency's two remote-sensing satellites, ERS 1 and ERS 2—using software developed at Caltech and JPL.

Of the four volcanoes, Hualca Hualca, in southern Peru, is especially worthy of close observation because it is in a well-populated area and just a few miles from Sabancaya, an active volcano. A second volcano, Uturuncu, in Bolivia, was found to be bulging at a rate of one to two centimeters per year, while a third, the Robledo caldera, in Argentina, is actually deflating. The fourth is a previously unknown region of surface deformation on the border between Chile and Argentina, christened "Lazufre" because it lies between the volcanoes Lastarria and Cordon del Azufre.

Besides revealing volcanic hazards, the study proves the mettle of a new means of tracking ground deformation. The fact that not one of the four volcanoes was known to be active—and thus probably wouldn't have been of interest to geophysicists conducting studies using conventional methods—shows the promise of the technique, Pritchard says. The data are superior to ground-based results in that a huge amount of subtle information can be accumulated about a large number of geological features.

Each satellite bounces a radar signal off the ground and measures the time it takes to return. On a later pass, when the satellite is again in approximately the same spot, it sends another signal to the ground. If the two signals are out of phase, then the distance from the satellite to the ground is either increasing or decreasing, and if the features are volcanic, then the motion can be assumed to have been caused by the movement of magma underground or by hydrothermal activity. "You can think of a magma chamber as a balloon inflating and deflating," says Pritchard. "So if the magma is building up underground, you expect a swelling upward, and this is what we can detect with the satellite data." With an appropriate satellite mission, all the world's subaerial volcanoes could easily be monitored on a weekly basis—an invaluable hazard-alert system for areas lacking regular geophysical monitoring.

Another unusual finding shows the method's promise for better understanding volcanism. The Lascar volcano, in Chile, has had three major eruptions since 1993, as well as several minor ones, and many volcanologists assumed there should have been some ground swelling as well, Pritchard says. "But we found no deformation, which could tell us interesting things about magma plumbing." There are several possible explanations: The first and most obvious is that the satellite passes took place at times between inflations and subse-

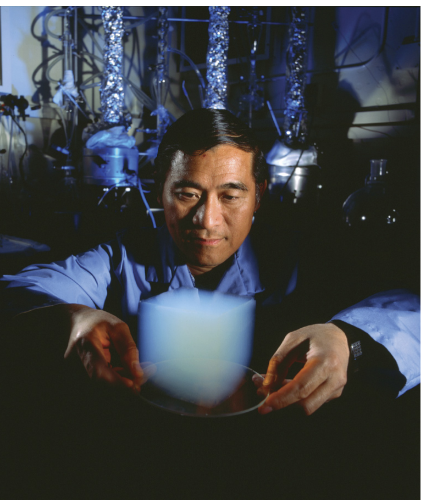


The four volcanoes, with the bands of color showing the amount of movement detected. The satellites actually measure ground deformation along their lines of sight, which are about 20 degrees away from vertical. The arrow labeled "LOS" in the lower right corner shows the direction in which the satellites were looking. (After Pritchard and Simons, *Nature*, volume 418, page 168.)

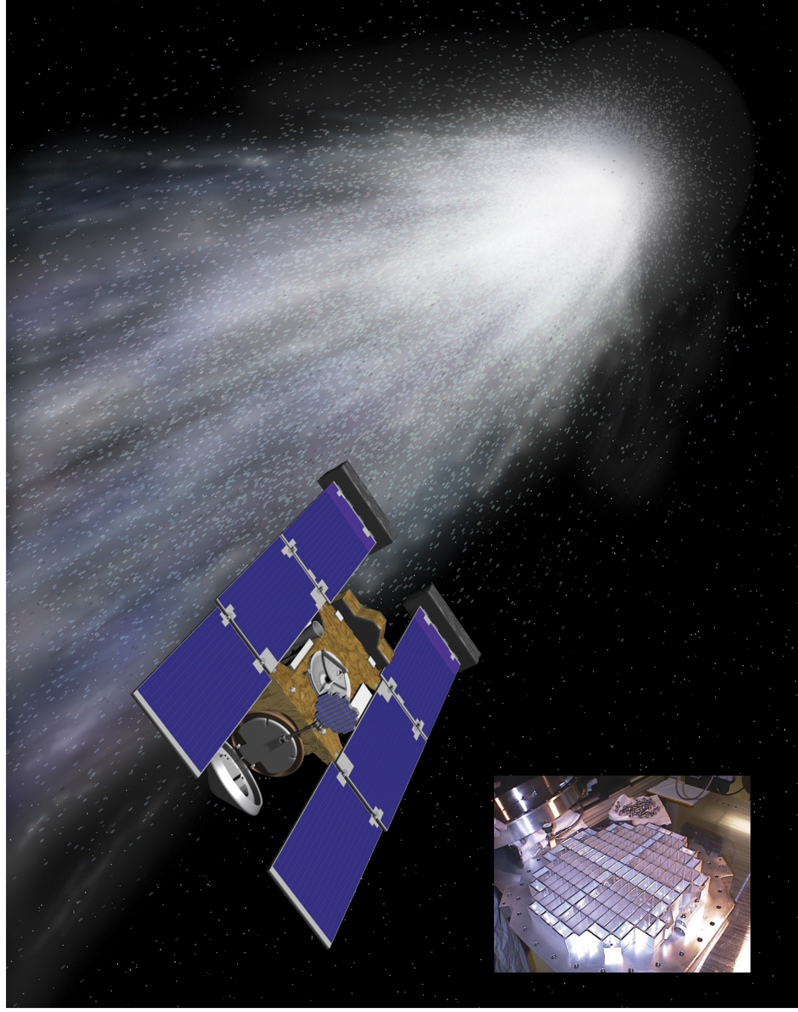
The White-Glove Test

Like a finger dragged across a neglected bookshelf, JPL's Stardust spacecraft is swiping up dust—rock particles finer than sand grains blowing through the solar system from the direction of Sagittarius. (You can actually see the stuff on a good night—it's the dark band running down the middle of the Milky Way.) On August 5, Stardust deployed its dust collector, which is shaped like an oversized tennis racket; the spacecraft took an earlier sample from February to May 2000. The racket is strung with a ghostly material called aerogel—a silica compound that is 99.8 percent empty space—a concept developed by Stardust's deputy principal investigator, Peter Tsou, to slow down and trap the fragile particles without damaging them.

Stardust is en route to a January 2004 meeting with comet Wild 2, where the racket's other side will be used in a backhand stroke to grab the first sample ever taken from a comet. Wild 2 never gets closer to the sun than the orbit of Mars, so the comet's ice and dust should be little changed from when it, and the rest of the solar system, formed more than 4.5 billion years ago. The sample-return capsule will be parachuted back to Earth in 2006. □—*DS*



Peter Tsou and an aerogel cube.



Comet Wild 2 will be safely past its active peak and on its way back into the deep-space deep freeze when Stardust catches up with it. The spacecraft will fly through the comet's coma, or dust cloud, about 150 kilometers in front of the nucleus. The inset shows the collector being filled with aerogel.

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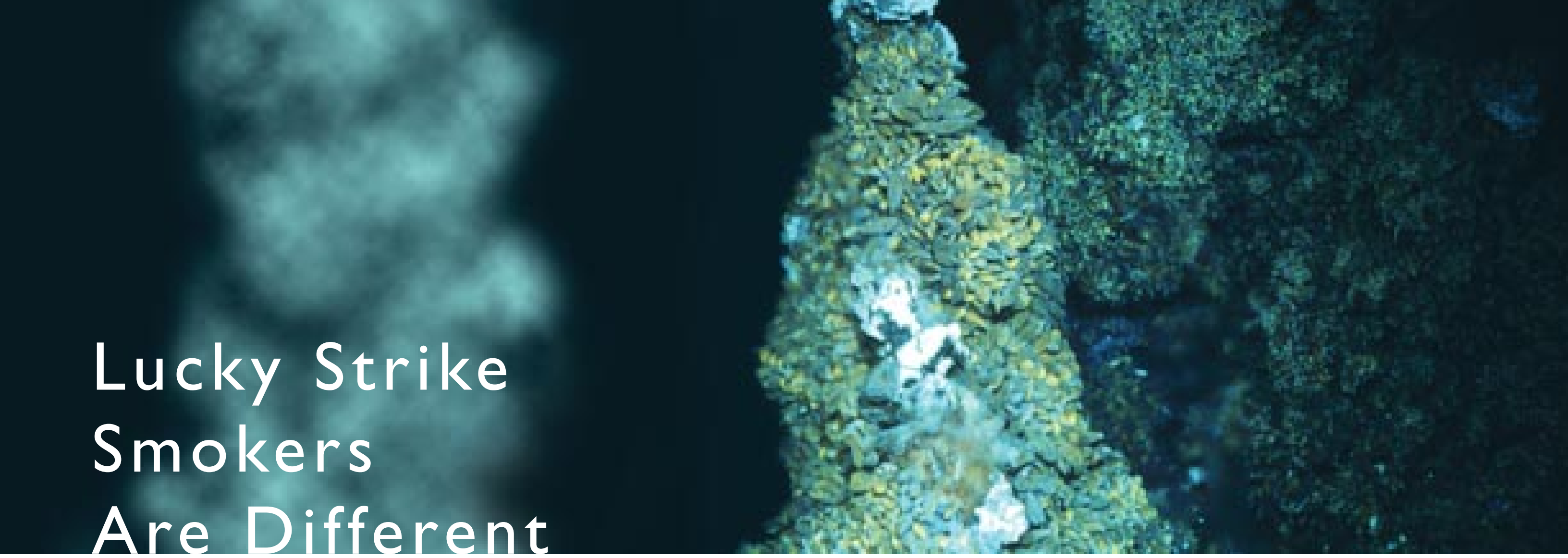
quent deflations, so that no net motion was recorded. It could also be that magma is somehow able to pass through the volcano without deforming it; or that the magma chamber is so deep that its deformations aren't visible at the surface.

The paper appeared in the July 11 issue of *Nature*. □—*RT*

Watson Lectures Set

Mark your calendar for this fall's lineup of Earnest C. Watson Lectures. The series leads off with Jack Beauchamp (BS '64), Ferkel Professor of Chemistry and former chair of the National Research Council Committee on Commercial Aircraft Security, talking about "Countering Terrorism: The Role of Science and Technology" on October 9. Henry Lester, Bren Professor of Biology, follows on October 23 with "The Response to Nicotine." Next Edward Stone, Morrisroe Professor of Physics and former director of JPL, chronicles "The Voyager Journeys to Interstellar Space" on November 6. Professor of Physics Nai-Chang Yeh looks at "Superconductivity—Resistance is Futile" on January 15, 2003. And finally, Associate Professor of Materials Science Sossina Haile explores "Fuel Cells: Powering Progress in the 21st Century" on January 29. As always, the lectures begin at 8:00 p.m. in Caltech's Beckman Auditorium, and are free and open to the public.



Lucky Strike Smokers Are Different

by Paul Asimow

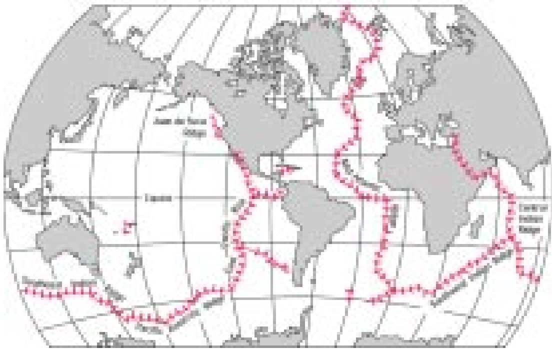
In the dredging bucket of *Atlantis II* was a new species of mussel, right, clinging to lumps of fool's gold (iron sulfide) and glassy lava.

Left: A forest fire in an overflowing ashtray? Not exactly. The "cigarette butts" are tubeworms, which live near volcanic vents below the Pacific Ocean. Called smokers, these vents belch out superheated water and assorted minerals. Smokers have been found along midocean ridges all over the world, but those at Lucky Strike (*not* named after a cigarette brand) are unique, with a different geology, vast numbers of mussels (top right), and not a tubeworm in sight.

On a pleasant September day in 1992, after the winter storms and before the hurricane season, a French-American science party aboard the research vessel *Atlantis II* was cruising up and down the Mid-Atlantic Ridge near the Azores looking for hot water vents at the bottom of the ocean. Navigating by real-time multibeam sonar, the ship arrived at a promising volcanic construction along the ridge. Instead of doing the vent search first, the scientists decided to lower a dredging basket for a rock sample. The dredge returned from 1,600 meters under the sea filled with live mussels and fresh sulfide minerals (above). This was quite unexpected: they didn't think they were near a possible vent site, and they'd never found these mussels before. In honor of its remarkably random discovery, the vent field was christened Lucky Strike. It's unusual in many more ways than mussels, and I'm trying to find out why.

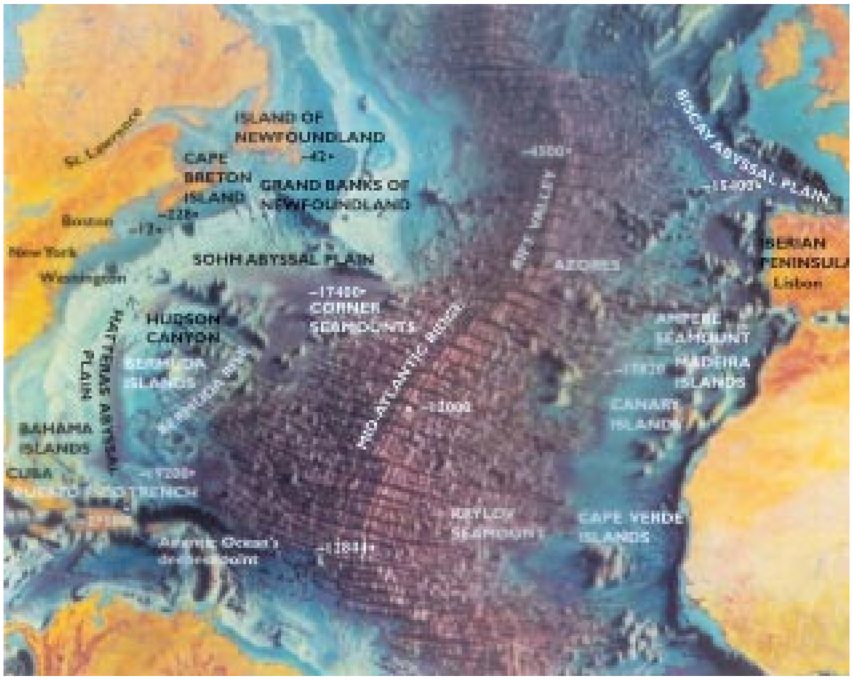
Anyone who studied geology more than 20 to 30 years ago probably learned only about the continents. They're very easy to study, because you can walk around on them. And they have a lot of history—many parts of the continents are billions of years old. But nowadays, all the interesting action is under the ocean, especially along the midocean ridges. These ridges are a global system of volcanoes about 40,000 kilometers long. They include the Mid-Atlantic Ridge, which runs right down the middle of the Atlantic Ocean; the East Pacific Rise (which spreads much faster than the Mid-Atlantic Ridge, adding about 10 centimeters of new crust a year, compared with two centimeters of new crust a year at the Mid-Atlantic Ridge); and the Southeast, Southwest, and Central Indian Ridges. Despite the faster spreading rate in the Pacific, the Atlantic Ocean is growing at the expense of the Pacific, because its margins are still attached to the continents rather than subducting (sliding) underneath them and returning to the mantle below. (I probably won't be able to say that any more in 100 million years or so.)

The artist's impression of the seafloor of the Atlantic on the next page shows the Mid-Atlantic Ridge to be quite a respectable mountain range, rising 2,000 meters above the abyssal plain (the flat ocean floor), which is generally about 5,000 meters deep. The depth of the crest of the Mid-Atlantic Ridge varies along its length: it's mostly around 2,500 meters deep, but as you go up toward the Arctic, it gets shallower, and even rises



The midocean ridges wind around the globe like the seams of a baseball. The ocean crust really is coming apart at the seams at these ridges.

From *Understanding Earth,* Frank Press and Raymond Siever, 1994, 1998, 2001, by W. H. Freeman & Co. Used with permission.



Map of the Atlantic Ocean floor showing the Mid-Atlantic Ridge as a sizeable mountain range, broken up into numerous segments by fracture zones called transform faults.

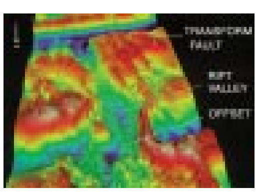
Right: The Thingvellir plains are part of the rift valley of the Mid-Atlantic Ridge, which runs above water across Iceland. The cliffs on the left side of the valley are on a tectonic plate moving toward America, while those in the upper far right distance are on a plate moving east. Volcanoes and geysers are active all along the valley floor.

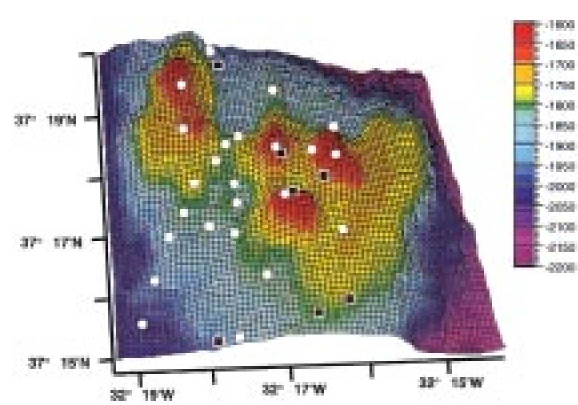
above sea level across Iceland. Iceland is the only place where you can walk around on the ridge without getting wet.

Looking more closely at the Mid-Atlantic Ridge, you can see in the model lower left that there's a 20-kilometer-wide rift valley running down the center of the mountain range, and that the ridge is broken into segments separated by deep cracks in the crust called transform faults, or fracture zones. All the midocean ridges are divided into these segments, and we don't really know how they form—it's an interesting puzzle. Are they just a geometric constraint of the way the earth is spreading? Are they due to preexisting weaknesses in the lithosphere (the cold and therefore brittle layer of rocks near the earth's surface), perhaps left over from the way the continents broke apart? Or are they generated by instabilities in the upwelling of the mantle underneath? Eventually, I would like to get at which of these possible causes are the most important.

If we zoom into the rift valley, we often find that there's a volcano sitting in the center. The Lucky Strike seamount (literally, mountain under the sea), below, is about 600 meters high, not tall enough to stick up out of the valley, but still a pretty big feature. And sitting on top of it are three active volcanic cones. They're very anomalous in composition, which is part of the story. The hydrothermal site I'm going to talk about is on the side of one of them.

The seafloor of the rift valley is covered with what are called pillow basalts, formed when basaltic lava erupts from below into cold water. As it emerges into the water, it tends to separate into blobs. The outside quenches into glass, while the interior crystallizes more slowly, and then these blobs pile up. You can find them on land in some places, and they're clear evidence that you're looking at something that used to be under water,

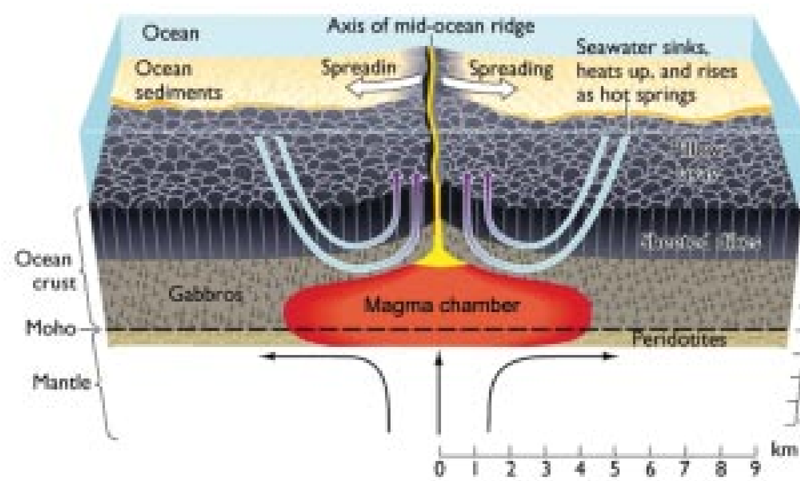




Above: Part of the Mid-Atlantic Ridge, with blue areas the deepest. A segment of the rift valley runs down the center, bounded by a transform fault at the upper end and a short offset at the lower. Right: The Lucky Strike seamount, a large volcano in the rift valley, is topped by three volcanic cones, the red peaks in the center, between which are the hydrothermal vent fields. (Black boxes: dredge sites; white circles: rock core sites).

Earth and Planetary Science Letters, 148, Langmuir et al., Hydrothermal vents near a mantle hot spot: the Lucky Strike vent field at 37°N on the Mid-Atlantic Ridge, 69-91. ©1997, with permission from Elsevier Science.

Right: All ocean crust—70 percent of the earth's surface—forms at the midocean ridges. Lava rises to the surface from the magma chamber at the ridge axis and becomes pillow basalt. It's very porous, so that sea water sinks through, heats up as it comes close to the magma chamber, and shoots back out onto the ocean floor as a hot spring, or hydrothermal vent.



A black smoker, above, and pillow basalt, below. Most of the seabed around the ridge areas looks as though it's covered with these pillows, formed when hot lava erupts into the cold seawater.

because we know of no way to make pillow basalts on land. There are also hydrothermal vents dotted around, where hot water comes out of the seafloor—imagine an underwater version of a geyser field in Yellowstone National Park. The one at left is called a black smoker: It's black because there are minerals dissolved in the water, mostly manganese oxides, and as soon as the water emerges from the seafloor, they precipitate out, so that you get clouds of black sediment shooting up looking just like dirty smoke pouring out of a chimney.

Now why would you want to study midocean ridges? I can give you a lot of good reasons. In the first place, that's where the entire ocean crust forms. While the active spreading centers themselves are very narrow (new ocean crust reaches its full thickness within a couple of kilometers of the ridge axis), a staggering 70 percent of the earth's surface is oceanic crust, and all of it has formed at a midocean ridge within the last 200 million years or so. The processes of crust formation at the ridges are relatively simple and reproducible, and this imparts a very characteristic structure to the entire oceanic crust.

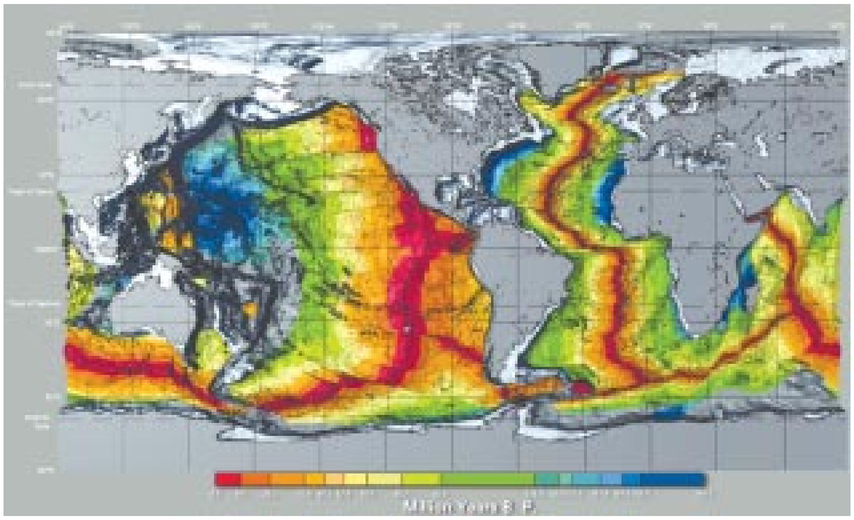
A cross section of a midocean ridge, such as the one in the diagram above, shows this characteristic structure: a sequence, from bottom to top, of mantle rocks such as peridotites, intrusive gabbros (granular igneous rocks that crystallize at depth), sheeted dikes (lava crystallized in the crack that was bringing it to the seafloor), pillow basalts, and sediments. This sequence was known from on-land geology since the beginning of the 20th century, in places where a midocean ridge has been pushed up on land, and it's called an ophiolite complex, which, incidentally, is a really bad two-language play on words: this type of rock when it gets altered forms serpentinite, and *ophios* is Greek for snake.

The tectonic plates carrying the continents are spreading apart at the ridges because of gravitational forces distributed across the plates and at all their edges. Locally, beneath the spreading ridge, the earth's mantle (the layer between the crust and the core, 2,900 kilometers deep) has to well up to fill the space. It's a popular misconception that the mantle is liquid. In fact, it's rock solid due to the high pressure of the rocks above pressing down on it. When the mantle is drawn upward by spreading at the ridge, the pressure drops, and it partially melts at depths between about 30 and (at most) 200 kilometers. The molten fraction can then separate and rise buoyantly up into the crust. It usually "ponds" at a shallow depth (a few kilometers), and sits there in what's termed a magma chamber, slowly cooling and crystallizing into igneous rocks.

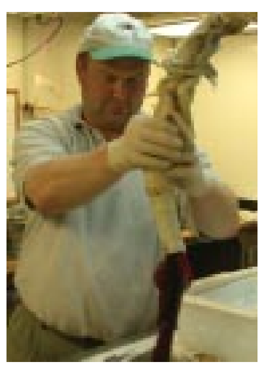
Occasionally, the ocean crust cracks all the way to the top, and lava (which is what we call magma once it reaches the surface) erupts onto the seafloor, spreading all around as pillow basalts. In the conduit where the crust cracked, the magma crystallizes and forms a dike. The plates continue to spread apart, the crust cracks again, another eruption of lava occurs, and another dike forms. Eventually, you get sheet after sheet of dikes transitioning upward into pillow basalts. Because the pillow basalts are very porous, seawater makes its way down into the holes, gets close to the magma chamber, heats up, and reacts chemically with the basaltic rocks, altering their composition. This water can't get into the magma chamber itself, so it's pushed up again to come out at a place of least resistance, near the axis of the midocean ridge where the crust is being pulled apart. The places where it boils out most vigorously are the hot springs, or hydrothermal vents.

A second reason for studying the midocean ridges is that the volcanoes here are grossly dominant over all other types of volcanoes on earth. If you're interested in volcanic rocks, this is the place to go: 20 cubic kilometers of new igneous rock are formed at the ridges every year. The continents average between one and two

Müller, R. D. et al. Digital Isochrons of the Ocean Floor, http://gdcinfo.agg.emr.ca/app/agemap_e.html



This digital map of ocean-floor age reveals how young the rocks around the midocean ridges are. Red areas are rocks formed less than 10 million years before the present (B.P.), and blue areas are rocks that formed in Jurassic times, 200 million years B.P. Because the East Pacific Rise is spreading particularly fast, the age bands on either side are quite wide.



Above, a colony of tubeworms at the East Pacific Rise and right, Woods Hole Oceanographic Institution biologist Tim Shank extracting a young specimen from its white chitin tube. Fully grown, tubeworms can reach eight feet.

Courtesy Galapagos Rift 2002 Expedition, funded by NOAA, NSF and WHOI.

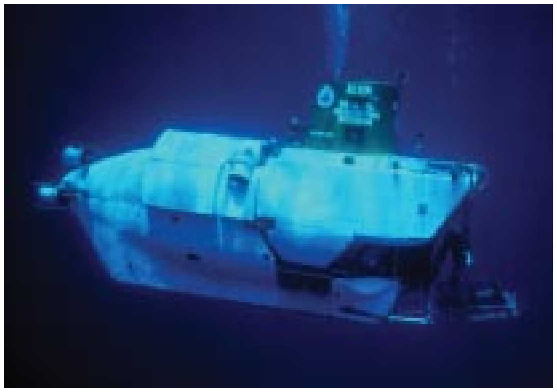
billion years old, but the seafloor is nowhere older than Jurassic, a mere 200 million years.

A significant fraction of the earth below sea level has been resurfaced within the last 10 million years, especially on the fast-spreading East Pacific Rise. So there's a lot of action going on down there—a lot of new rock being made, a lot of heat getting out of the interior of the earth, a lot of chemical differentiation going on, and a lot of interesting events to study.

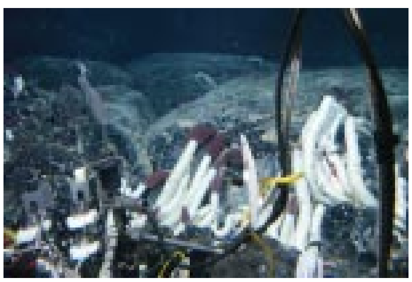
Third, and my best reason, is that as volcanic systems go, it's the simplest. A classic problem in petrology is to separate the effects of the process of melting from the effects of the source composition (what was in the rocks that were melted to make the magma that cooled to make the rocks we're studying). At the ridge, this is a fairly tractable problem because there's no preexisting overlying crust to alter or contaminate what's coming out of the upper mantle, which appears to have a reasonably homogeneous source composition. Moreover, because the ridges are under a few thousand meters of water, and therefore under a few hundred bars of pressure, the volatile chemicals that come out of volcanoes—things like water, carbon dioxide, noble gases, methane, hydrogen, and hydrogen sulfide—actually stay dissolved in the glass that forms the rims of the basalt pillows. It's much easier than studying volcanoes on land, where all these chemicals are spewed into the air when the water coming out flashes over into steam, often explosively. Which brings me to a fourth excuse for studying undersea volcanoes: it's relatively safe!

A fifth, and very important, reason for studying midocean ridges is that they control the chemistry of the ocean water itself to a significant extent. For example, ocean water usually has a magnesium concentration of 53 millimoles per liter, but there's no magnesium at all in the hydrothermal fluids coming out the vents. And that's because the ridges are the major sink for magnesium in the

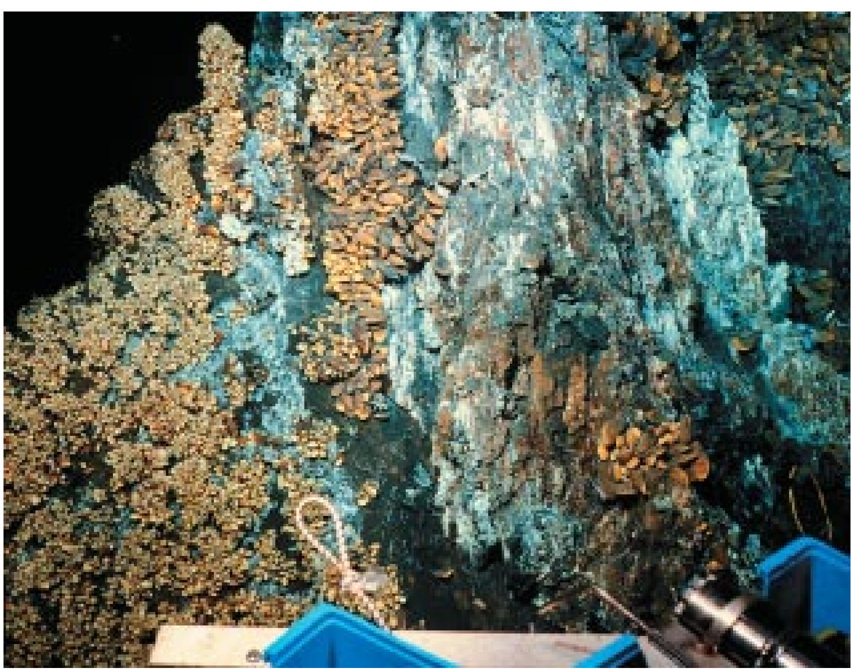
Right: ***Alvin,*** **the deep-submergence vehicle operated by WHOI, can take two scientists and a pilot to a depth of 14,700 feet and is packed with robotic arms, sensors, sampling baskets, cameras, and 12 powerful lights for illuminating the seafloor.**



When *Alvin* revisited the tubeworm-rich vent site "Rose Garden" in the Galapagos Rift earlier this year, the tubeworms were gone, and the area was coated with fresh lava, as in the scene on the left. But a very young tubeworm colony was starting up at a nearby site, named "Rosebud," lower left. Below: *Alvin* approaching a vent at Lucky Strike. Tubeworms are absent, and mussels coat almost every surface. Their shells are white, but a coating of iron hydroxides makes them look rusty.



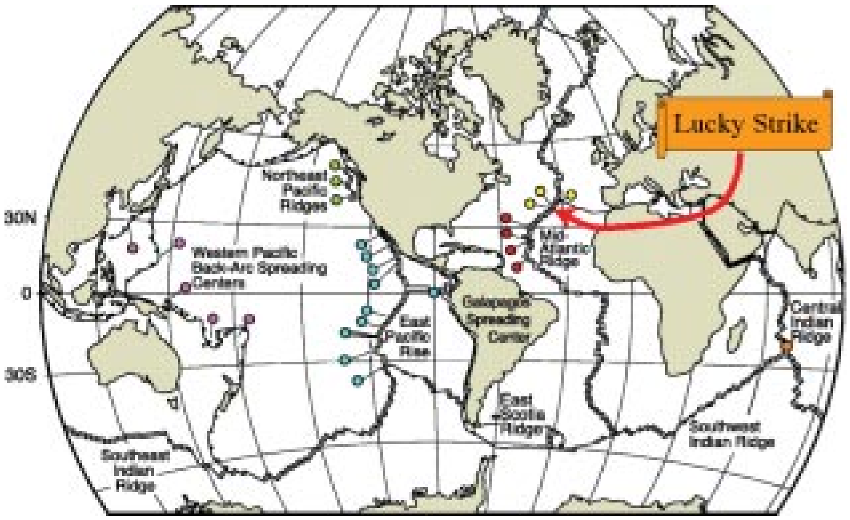
Courtesy Galapagos Rift 2002 Expedition, funded by NOAA, NSF and WHOI.

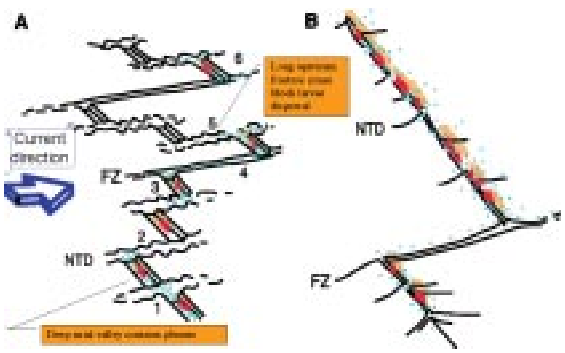


oceans. It weathers off the continents, gets into the oceans via the rivers, sinks through the porous pillow basalts into the crust, and stays there. It's true of a number of other elements as well, but clearest for magnesium.

Finally, but perhaps most surprisingly, there's life down there. In the total absence of sunlight, there are biological communities that live on these volcanic systems. One of the most amazing discoveries of the last 50 years was made in 1977 by Robert Ballard in the Woods Hole Oceanographic Institution (WHOI) deep-submergence vehicle *Alvin*. When he dived down to a hydrothermal vent near the Galapagos Islands, he found a whole ecosystem down there, including bacteria, tubeworms, shrimp, crabs, mussels, clams, octopuses, and fish—everything but plants. Until this find, no one knew that it was possible to have biological communities that were not based on photosynthesis. The animals are feeding on bacteria that get their energy from reactive chemicals in the hot water coming out of the vents. Heat coming out of the earth can provide energy to support life, just like heat from the sun can. It's life, but it's a hard life. It requires some pretty fancy biological tricks to exploit these chemical reactions for metabolism, and most organisms can tolerate only a limited range in temperature. Each species needs to find the right distance from a high-temperature vent, and when the vent position shifts, they're likely to get cooked (there's a spot on the ridge known as the tubeworm barbecue), frozen out, or covered in lava. It's now become a popular belief that these deep-sea vents may have been where life originated—as hostile as they seem to us, they would have been a much less hostile environment than the earth's surface four billion years ago. And, by the way, evidence for a liquid water ocean beneath the ice on Jupiter's moon Europa has excited a great deal of speculation, because hydrothermal energy sources could make that world one of the only other places in the solar system able to support life.

Being a geologist and not a biologist, what I want to know is this: At what level of detail do the physical and chemical variations among the midocean ridges control where the hydrothermal sites are, what kind of vents develop, and what sort of biological communities live on them? How does the physical shape of the ridge system, and the frequency of the volcanic events there, control the opportunities for life to survive? The animals can exist only in a habitat having a stable heat source that goes on for a long time. Does the structure of the ridge also control the opportunity for life to move from one place to another? If you can only live along the rift valley, your opportunities to migrate from one active vent field to another may be limited by the geography. As shown on the map on the next page, the East Pacific Rise has a lot of vent sites and is one entire





Above: Colored lollipops mark known hydrothermal vent sites along the major midocean ridges, with a different color for each biogeographic province, areas where the same animals are found at each site. Right: It's much easier for the larvae of vent animals to spread along the East Pacific Rise ridge zone (B) than along the Mid-Atlantic Ridge (A), which has more fracture zones (FZ) and offsets (nontransform discontinuities, NTD) as well as steeper cliffs edging the rift valley, which trap the vent plumes. Blue dots identify vent animal larvae distribution; red triangles, active vents; orange areas, hydrothermal plumes.

biogeographic province—you find the same organisms wherever you go—but the Mid-Atlantic Ridge has two distinct biogeographic provinces right next to each other, with essentially unrelated organisms and different biological communities. Why is this? One possibility is that, because the fast-spreading East Pacific Rise has relatively few fracture zones—called transform faults—and they're relatively short, it's quite easy for organisms to move up and down it. Moreover, because the rift valley of this ridge is very shallow, the hydrothermal plumes carrying live bacteria and animal larvae can get out of the valley and spread in the general ocean currents. The Mid-Atlantic Ridge, in contrast, has a 1,500-meter-deep rift valley, which the plumes can't rise out of. And there are lots of long fracture zones, which the bacteria and larvae can't get past. Because of this physical isolation, the next ridge segment could have a completely different biological community.

A second possibility, and one that I favor, is that different biological communities, if they can get to a particular ridge segment at all, are responding to chemical differences between midocean-ridge rocks when they decide where to set up camp, and when the different organisms begin fighting over resources. The rock chemistry affects the chemistry of the hydrothermal fluids that come out through the vents, which controls the mineralogy of the deposits at the vents, and hence the elements available to the bacteria as a source of energy. Different elements are used by different species of bacteria, and different populations of animals feed on them.

How do we find these vents? It's actually quite hard. To study the surface of the earth you can fly around in an airplane, and see very large areas very clearly, or you can fly a satellite overhead, and see the whole world. The reason the bottom of the ocean is the last frontier is that it can't be viewed from the air or from a surface ship, because seawater absorbs any sort of electromagnetic radiation such as light, radio, and radar. Sonar is too coarse a tool to find these little vents until you're already close, while the area you can observe out of a small submersible is so tiny that using one to look for vents would be like exploring a map of the world with an electron microscope. But we have our ways.

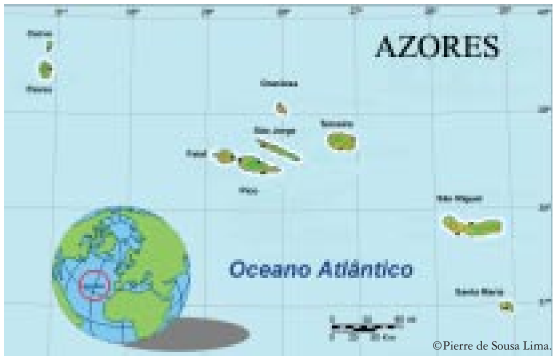
The first is to look at the water chemistry. Water is sampled by dropping a long cable off the side of a ship; attached to the cable is a series of buckets triggered to close at different depths, a method called hydrocasting. Because hydrothermal water is rich in certain metals, like manganese, an increase in the concentration in a sample can point to a vent. It's also very cloudy, something you can measure with a nephelometer, a tool that transmits light across a few centimeters of seawater and measures how much is absorbed

Another way is by doing a seafloor magnetic survey. Fresh igneous rock is magnetized, but at a vent site the hot water flowing through the rock destroys the magnetic minerals, so that a bull's-eye of low magnetization indicates hydrothermal activity—although it can't tell you whether or not the vent is active.

There's also acoustic scintillation tomography, a catchy phrase for something similar to what bats do when they use echolocation. If a bat sends out two clicks and notices a difference between the echoes, it knows a tasty bug is moving nearby. If we send two sonar pings out from a fixed buoy or stationary submarine,

The striking Eiffel Tower smoker vent at Lucky Strike is 20 meters tall. Almost every part is encrusted with mussels.

The Azores are an archipelago of volcanic islands formed by a hot spot. The active hot spot is east of the Mid-Atlantic Ridge, but a couple of older islands on the west side of the ridge have been separated from the others by continued seafloor spreading at the ridge axis. Below: One way to find hydrothermal vents is to tow a magnetometer along the ocean floor. Hot water demagnetizes the rocks, so that a blue bull's-eye of low magnetization can reveal a vent site—though it could be a dead one.



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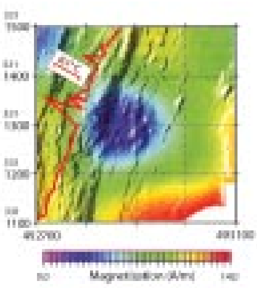

Johnson, H. P. et al., *EOS*, 83, 73-79 (2002)

and they travel through even a small area where hot and cold water are mixing vigorously, they come back decorrelated. This can pinpoint the possible location of a vent to within meters in an area of one square kilometer.

And then there's the dumb-luck method, which is how the Lucky Strike segment was found. The FAZAR expedition on *Atlantis II* (FAZAR stands for French American ZAPS and Rocks, and if that still doesn't mean much, ZAPS stands for Zero-Angle Photon Spectrometer, an instrument to measure manganese in seawater), was supposed to find the hydrothermal sites with ZAPS, and also to explore how the geochemistry of rocks along the ridge was affected by the proximity of the Azores archipelago. When the ship got to Lucky Strike (no one had ever been there before, because every previous cruise had picked a parallel extinct rift, thinking it was the axis of the ridge), the scientists took one dredge before taking water samples, and pulled up the live mussels and fresh sulfides shown on page 9. It's the least efficient way possible to find a hydrothermal site, yet in this case it worked. A return cruise was organized with *Alvin* to explore this little postage stamp of an area, and they found a field of vents. Some of the cooler-looking ones were named Eiffel Tower, Statue of Liberty, and Sintra (a beautiful part of Portugal, whose national waters surround the Azores).

The water coming out of these vents is at 330 degrees Celsius. On the seafloor this isn't boiling, because of the high pressure, but it's still very hot. And the black smoker chimneys here, unlike most others in the world, are not built of sulfide minerals but of barium sulfate, aka barite. The animal community is dominated by mussels, whereas many other vent sites are dominated by large tubeworms. It's an entirely new biogeographic province.

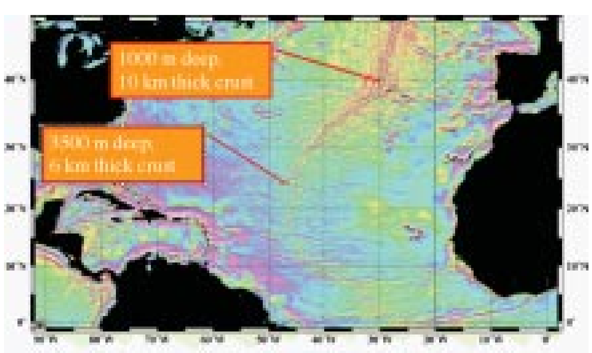
Why is this hydrothermal vent different from all the others? This is where I come in: I'm a specialist in igneous rocks, and I think that geochemistry can explain a lot about why there's a different community of life forms at Lucky Strike.

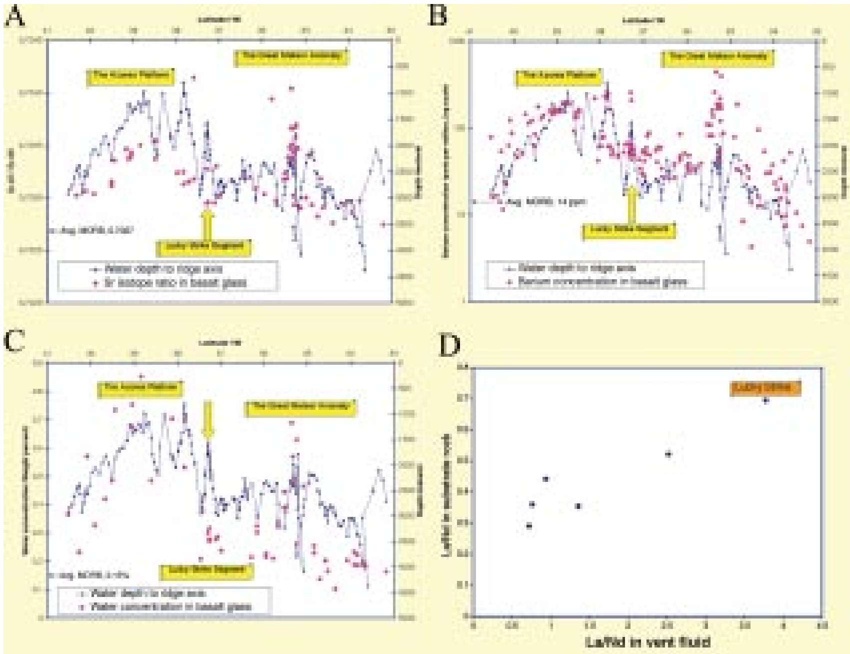
Although most midocean ridge rocks are about the same, because the mantle source is rather homogeneous and the spreading process is everywhere similar, exceptions occur near hot spots—volcanic sources that are fixed in one place while the earth's plates move over them. The most famous hot spot is the Hawaiian Islands, which get progressively older the further away they are from the current vent of the volcano, on the edge of the Big Island. Some hot spots are near ridges and interact with them, and one of these is the Azores, a cluster of nine islands belonging to Portugal that straddle the Mid-Atlantic Ridge.

Hot spots affect ridges in several ways. The first is obvious in the map of seafloor depth shown below. The axis of the Mid-Atlantic Ridge is normally about 3,500 meters deep, with an igneous crust about six kilometers thick, but going up toward the Azores, the ridge is only 1,000 meters below sea level, and the crust is 10 kilometers thick. Crustal thickness is just a reflection of how much basalt has been made, so that there must be more mantle melting near the Azores. The depth to the ridge axis, in turn, reflects the density of the underlying rock column—since crust is less dense than mantle, areas of thick crust stand higher, a principle called isostasy, which is just Archimedes' principle applied to the earth's rigid upper layers floating on the ductile interior.

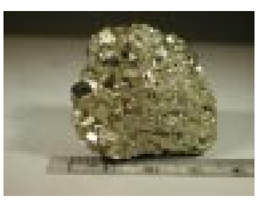
The second effect is that the chemistry is anomalous in several ways. The first anomaly is in the radiogenic isotope ratios, which are the ratios of different isotopes of things like lead, formed by the radioactive decay of things like uranium. These are some of geochemists' favorite and absolutely most obscure tools (*E&S*, 1997, No. 1, p. 20). In graph A on the next page, you can see that the strontium 87/86 isotope ratios at Lucky Strike and the Azores are higher than for ordinary midocean ridge basalt (MORB). It's a sign that we're looking at old, recycled crust: rocks that were enriched in rubidium relative to strontium (^{87}rubidium decays to ^{87}strontium with a half-life of 48 billion years) by melting a long

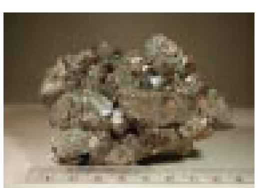
Around the Azores, the Mid-Atlantic Ridge comes much closer to the surface of the ocean, as this marine gravity map of the depth of the seafloor shows.





The strange chemistry of sites along the Mid-Atlantic Ridge near the Azores: A, strontium 87/86 ratios; B, barium levels in the rocks; C, water dissolved in the basalt glass; D, ratio of lanthanum (La) and neodymium (Nd) in the substrate rock compared with that in the vent fluid. The blue lines in graphs A through C are bathymetric depth, and Avg. MORB is the average value for ordinary midocean-ridge basalt.





Lucky Strike smokers are made of barium sulfate (barite), top, whereas other smokers are mainly sulfides such as iron sulfide (iron pyrites or fool's gold), center, or zinc sulfide (sphalerite), bottom.

time ago, subducted back into the mantle, mixed around, and brought back up by the Azores.

In addition to strange isotope ratios, the rocks near the Azores have very strange trace-element concentrations, enriched in some cases by factors of hundreds. The concentration of barium in the rocks, for instance, changes from 14 parts per million (ppm) in average basalt to 50 or 60 ppm in the Lucky Strike segment, and up to 200 or 300 ppm near the Azores (graph B).

Moreover, the rocks themselves are very rich in dissolved water as you approach the Azores (graph C): ordinary basalt is about 0.15 percent water by weight, but in the vicinity of the Azores it gets up to one percent water, which has all kinds of wonderful effects on the way the mantle melts and the chemistry evolves.

The unusual composition of the lava is reflected in the chemistry of the water coming through the hydrothermal vents. Remember, this is seawater that soaked through the porous crust, got close to the magma chamber, heated up, interacted with the rocks down there, and flowed back up again. It inherits the chemistry from the rock that it interacts with, and we can see evidence of this inheritance by looking at the ratio of two rare-earth elements in vent fluids and the volcanic rocks dredged nearby. You can see from graph D, above, that Lucky Strike is definitely wacky, both the rocks and the vent fluid.

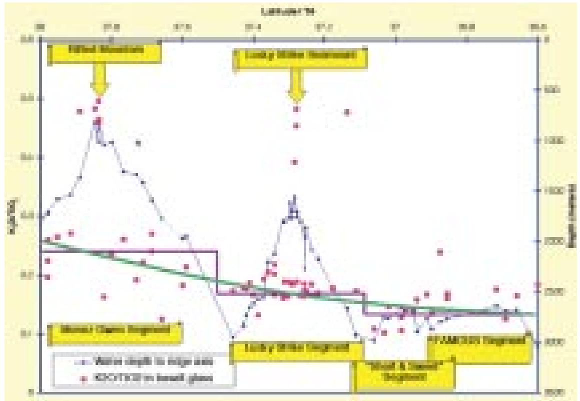
The rocks are weird, the water is weird, and the minerals that precipitate out of the water are weird. Nearly all the black smokers in the world are made of sulfides, mainly of iron, zinc, and copper. (Iron sulfide smokers are just big piles of fool's gold). They can accumulate into massive sulfide deposits, which can be very important economically if by some chance the seafloor ends up on land. A huge black-smoker-related sulfide deposit in Oman drove the entire Mesopotamian Bronze Age until the copper ran out. Lucky Strike smokers are different: they're made from sulfates, mostly barite, the mineralogist's name for barium sulfate.

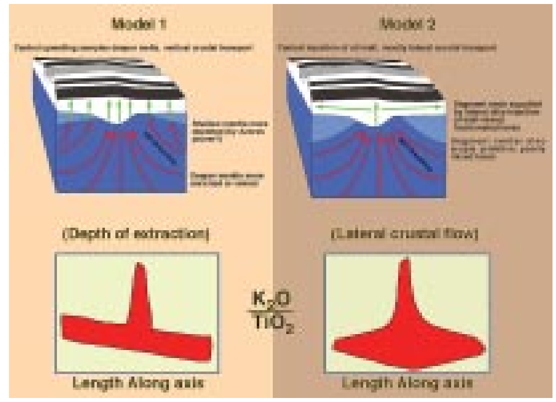
The mineral substrate and water chemistry in turn affect the microbial ecology of the smoker columns. As I explained earlier, there are bacteria down there that get their energy by oxidizing sulfides into sulfates, and others that get their energy by reducing sulfates to sulfides. In the absence of plants, which can't grow down there because there's no sunlight, these bacteria form the basis of the entire food web. Sulfate-reducing bacteria and sulfide-oxidizing bacteria use different metabolic pathways to provide organic carbon to their hosts, and function well in symbiosis with different animals. At Lucky Strike, the bacteria are living on barite, a big source of sulfate, which may be the reason that mussels are so dominant in this place.

Finally, I want to close with the question I raised earlier—why is the Mid-Atlantic Ridge segmented? Is the segmentation imposed from above by the crust, or from below by the mantle? The Lucky Strike segment is a really good place to look at this because there are chemical signals associated with the structure of the segment and the proximity to the Azores that I think will allow us to tell the difference.

Let's zoom out a bit from the Lucky Strike segment and look at the water depth and potassium/titanium ratio in basalt glass (another obscure geochemist's ratio that shows the influence of the hot spot) for four adjacent segments increasingly distant from the peak of the Azores platform at a latitude of 39.5 degrees north: Menez Gwen, Lucky Strike, "Short and Sweet," and FAMOUS. You can see from the graph on the opposite page that there's a regional gradient

Right: With the Azores to the left, and moving south along the Mid-Atlantic Ridge, the potassium/ titanium ratios have been plotted at four ridge segments. The ratio spikes in the middle of some segments. Far right: Model 1 would produce a gradient in the potassium/ titanium ratio, with a spike in the middle of each segment, and a smooth downward gradient along the segments as they get farther away from the Azores. Model 2 would give segments that all have a constant composition (but also with a spike), and the potassium/ titanium ratio would look like a staircase. Are the values in the graph best joined by the green gradient or the purple staircase? It could be either: the data aren't good enough. We need better measurements.





of decreasing potassium/titanium ratio with increasing distance from the Azores, and you can also see, superimposed on the gradient, that the ratio spikes in the middle of some segments. We've come up with two models to explain this.

In Model 1, the mantle flows up more in the middle of a segment, where the crust is thicker, and comes up from further down in the earth. This deeper part of the mantle might be more enriched in potassium than the shallower parts, which may have been depleted by the Azores hot spot, hence the spikes. If this is what's going on, then the north side of each segment, closer to the Azores than the south side, should have more of the "Azores signature," and we should expect to see a regional gradient (except for the spike) expressed within each segment. We should also see a smooth downward gradient along the four segments as they get farther away from the Azores, the green line in the graph.

The alternative hypothesis, Model 2, is that essentially *all* the magma is added to the crust in the middle part of each segment, where it can either erupt as lava onto the seafloor, showing its full range of compositional diversity (as reflected by the potassium/titanium ratio), or the lavas can get mixed up in magma chambers and then be forcibly injected sideways along lateral dikes in the crust. We know this happens because we've actually been able to see it with sonar: during a dike injection event, the sonar and seismic signals propagate along the seafloor for several kilometers. If this is what is happening, each segment would have a relatively even composition, except for a spike in the middle where the near-primary mantle melts can emerge unmixed. In this model, the potassium/titanium ratio would be a staircase, the purple line on the graph.

Is there a gradient or a staircase? Unfortunately, it could be either—the data are too noisy. This research was done 10 years ago based on a cruise that was focusing their sample collection on different issues, and we really need to go back and get more measurements, particularly at the ends of the segments.

To sum up, the Lucky Strike segment shows how many of the earth's systems are linked. An anomalous mantle chemistry caused by the nearby Azores hot spot leads to an anomalous crustal thickness, ridge axis depth, and rock chemistry, which in turn causes an unusual hydrothermal flow with an odd water composition, which produces strange vent chimneys. And all of this leads to a unique biogeographic province. A lucky strike indeed. □

Assistant professor of geology and geochemistry Paul Asimow grew up in Los Angeles, but earned his bachelor's degree on the East Coast, completing an AB at Harvard in 1991. The Southland must have lured him back, because he came to Caltech for his graduate studies, gaining an MS in 1993 and a PhD in 1997, as well as the Richard H. Jahns Teaching Prize in 1995. After two years as a postdoctoral research fellow at the Lamont-Doherty Earth Observatory of Columbia University he returned to Caltech in 1999 to take up his present position. A keen piccolo, flute, and tuba player as well as a music arranger and conductor, he may be most visible on campus as the associate conductor of the Caltech-Occidental Concert Band. But for many people around the world, he is best known for his inexplicable Web page of snowy owl photos. This article is adapted from a talk given on the 65th Annual Seminar Day in May.

PICTURE CREDITS:
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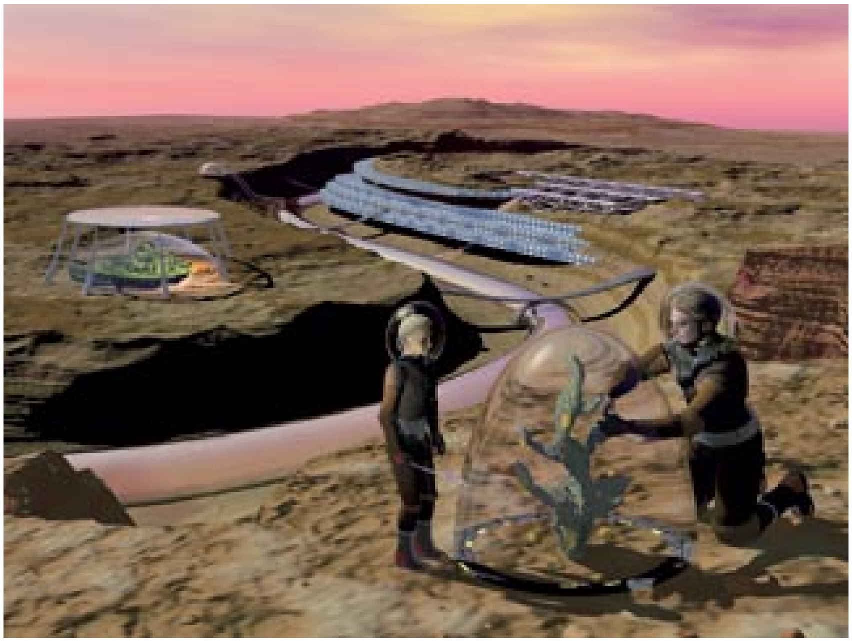
Rocket Science and Art: Travels with Charley

by Douglas L. Smith

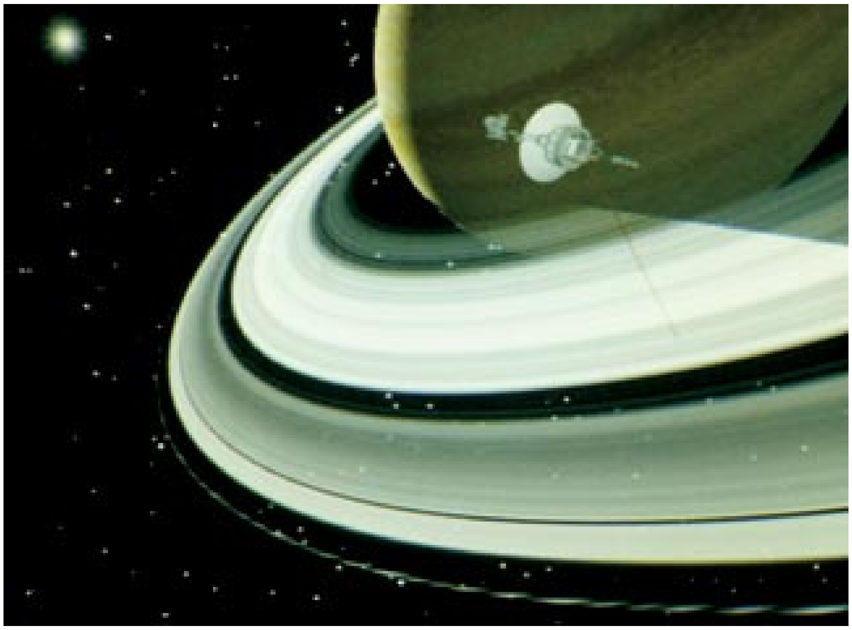
Charley Kohlhase's artistic career has run from nature photography through digital image manipulation to the creation of virtual worlds. *Yucca*, far left, is an unaltered close-up of the plant's bracts, or leaflike structures. *Between Two Worlds*, left, is a late-afternoon shot of Los Angeles's Griffith Observatory. The image was digitized and changed to sepia, and a reddish tint was added to the sky. A poster-sized version of the original, color image will be on permanent display at the observatory when it reopens in 2005. And *Canyon City, Mars*, below, is a 3-D landscape. An animation seen from the point of view of someone flying through the scene is available at http://mars.jpl.nasa.gov/spotlight/charleyKohlhase.html.



Charley Kohlhase joined JPL in May 1959 as a junior engineer in the trajectory-design group. He recalls one of his first assignments: "I was nearly 25 in the spring of 1960, and I was to give a presentation to a dozen colleagues on the possibility of sending a spacecraft to Mars, when in walked Drs. William Pickering {JPL's director} and Wernher von Braun, the latter radiating brain waves … had it not been for my youth, my heart would have given out at that moment. I arose on wobbly legs, stumbled to the board, and watched my life pass in front of me. I can still see the two broken pieces of chalk on the blackboard rail. With a shaky hand, I drew two sun-centered circles and the Hohmann transfer ellipse—one end tangent to Earth's orbit at departure and the other tangent to Mars's orbit at arrival—trying desperately to keep my chalk strokes clean and even. The next 30 minutes passed in a daze."

Kohlhase survived this first brush with greatness and went on to rise through the ranks. He led the trajectory, navigation, and mission design teams for Mariners 6 and 7 to Mars in the '60s. He did that *and* the overall system design for the Viking Mars orbiters/landers in the '70s, ensuring that all the components meshed. He then served as mission design manager for the Voyagers' Grand Tour of Jupiter, Saturn, Uranus, and Neptune. (See http://www.planetary.org/voyager25/stories-charlie-kohlhase.html.) And his last job before "retirement" in 1998 was science and mission design manager for Cassini–Huygens, scheduled to arrive at Saturn in July 2004.

Trajectory design and mission design go hand in hand, and the Grand Tour is a classic example. A flyby uses rocket science from the 1600s—Kepler and Newton have given you a group of curves, called conic sections because you can make them by slicing into a cone at various angles, to work with. You depart Earth on a hyperbola, segue into an ellipse around the sun, and approach your destination on another hyperbola. Then you can whiz



A frame from the groundbreaking 1981 animation of Voyager 2's flyby of Saturn. Saturn's atmosphere and ring system, including the narrow, braided F ring, were rendered as photorealistically as possible, incorporating the discoveries made by Voyager 1. All the stars, including the sun, have their correct positions and brightnesses. This summer is the 25th anniversary of the Voyagers' launches; by now, an estimated one billion people around the world have seen these animations.

on by, or you can settle into orbit—another ellipse, or possibly a circle. All you need is enough fuel to leap from one conic to the next, which can be quite a lot. Getting to a distant planet in a vehicle light enough to launch requires assembling many conics into a clever, roundabout route that gets gravity assists—the so-called "slingshot effect"—from passing close by other planets. "In the case of Voyager's assist by Jupiter," says Kohlhase, "the spacecraft gained 35,700 mph relative to the sun, while mighty Jupiter was slowed by only one foot per trillion years—hardly enough to affect Earth's weather, unless you chat with those picky chaos-theory folks."

The Grand Tour was the most ambitious carom shot ever conceived. "Multiplying the total number of possible launch days by the total number of different arrival dates at each of the four planets gave us some 10,000 possibilities to consider," which Kohlhase and his team winnowed to a set of 110. "The moon Io was top priority at Jupiter, and Titan top priority at Saturn. The game was to ensure that these primary targets were always encountered safely and at the best possible geometry, while picking up as many of the other moons as possible and staying close to the gravity-assist corridor to avoid expending propellant we'd need for subsequent flight-path corrections. We sought good communications with Earth, acceptable navigation sensitivity to errors, good viewing and lighting angles for the cameras, and adequate time spacing for each spacecraft to execute its assorted activities. We made sure that the later-arriving Voyager 2 could pick up important observations that might be missed by Voyager 1, while still enhancing the combined science if both craft were successful. And if Voyager 1 captured the Titan observations at Saturn, then the later-arriving Voyager 2 would be directed to Uranus and Neptune, focusing on the mysteries of those remote worlds—with a close dive over the Neptune 'polar crown' to fly past the large moon Triton a final plum."

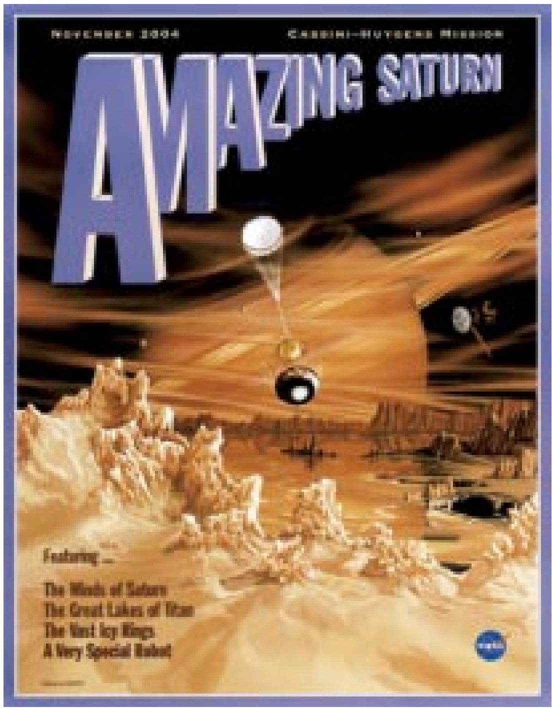
All the grunt work—tracking the planets and moons in their orbits, and plotting the spacecraft's path—was done by computer, of course, but in those days graphic displays were in their infancy and Kohlhase's visual intuition (he had wanted to major in architecture, but couldn't afford the five-year program and settled for physics instead) was given free rein. "I solved problems by combining the equations of rocketry with the 'look' of the orbits around other planets, the gravity and thrust vector diagrams, the way the spacecraft's subsystems interacted, and the multipath, branch-tree diagrams essential in assessing countless mission outcomes and their probabilities … I lived and breathed this job, often awaking in the wee hours with answers to problems my brain had been processing while asleep. I got so I could hear a problem stated and 'see' the answer, often within seconds."

Kohlhase wanted the public to share the movies of the flybys he saw in his mind's eye, so he recruited computer-graphics pioneer James Blinn, then a freshly minted PhD from the University of Utah. Blinn created the modeling and effects software—which originally ran on the microscopic brain of a DEC PDP-11/55—and Kohlhase composed each scene and supplied the commands the spacecraft would be seen to execute. The computerized spacecraft, "built" from more than 6,000 polygons whose vertices were derived from the real one's blueprints, was moved along its proper trajectory in small increments, and "key frames" where actions began or ended were adjusted as needed. Then the full animation would be run in "wire-frame" mode—drawing the polygons but not filling them in—to iron out any final kinks before adding color. (Wire-frame animation was as good as it got before Blinn arrived.) Blinn and Kohlhase later reunited to do several computer-graphic special-effect sequences for PBS's *Cosmos*. In fact, *Cosmos* creator Carl Sagan nominated the work for an Emmy of its own, says Kohlhase, but there wasn't a category for it back then.

This was long before NASA began formal outreach programs. "It just came naturally with being a mission designer," Kohlhase says. "I knew where the trajectory lay, and how the planets were lit, and I could draw clean diagrams whose perspective looked right. So I was always working with graphic artists to make these nice pictures for the folks at NASA HQ and various publications, and the artwork eventually became the animations."

Kohlhase was also the science and mission design manager for Cassini. This was to be the last of the giants, with four gravity assists en route, followed by 45 close passes by Titan during the four-year primary mission to guide the spacecraft's tour of the Saturnian system. But his official duties now included outreach, and more and more of his time was going into creating art for science.

Courtesy of Entertaining Solutions



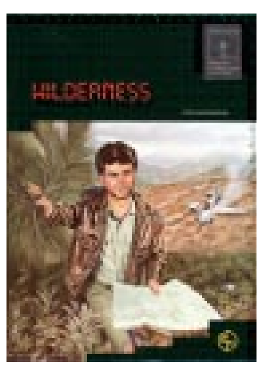
Along with the usual brochures, educators' guides, and Web sites, Cassini's outreach program under Kohlhase produced some more exotic products. At left is a postcard (later a wildy popular poster) Kohlhase patterned after the classic sci-fi magazine *Amazing Stories.* Craig Attebery did the artwork. And above is a development still from *2004—A Light Knight's Odyssey*, showing Dave the photon, voiced by John Travolta (right); and Milton, a prospector on Saturn's moon Mimas, voiced by Robert Picardo. The video is still a work in progress.

Below is a 12- by 20-foot mural designed by Kohlhase and executed by eight East L.A. artists, aged 8 to 17, of the Academia de Arte Yepes. Saturn, a Roman god of agriculture (hence the scythe) lifts the veil of mystery from the Saturnian system as the spacecraft arrives. And spacecraft team members have been signing their handiwork for decades, but the advent of digital media has allowed the general public to join in. In the photo at right, Kohlhase (left) and Richard Spehalski, Cassini's program manager, hold a DVD containing 616,420 signatures from 81 countries. Kohlhase's design for the disk includes the flags of the 28 countries that sent the most signatures as well as six wing feathers from a golden eagle, symbolizing both the attributes of the bird and the power of the pen. (See *Air&Space*, February/March 1999, for the full story.)

Kohlhase has hiked the back country from Patagonia to the Yukon, taking pictures as he went. ***Far North***, above, shot at 4:30 a.m. on a summer's morn in southeast Alaska, appeared in the 1994 ***Photographers' Forum*** "Best of Photography" annual. And less than an hour's drive from Pasadena, the view ***From Baldy Saddle***, left, often affords spectacular sunsets when haze from the L.A. basin infiltrates between the ridges to give a layered, painterly look.

An avid photographer, Kohlhase is never without a camera no matter how close to home he is. The *Droplet*, at left, encases a mountain mahogany bud he found a block away.

This first-hand experience of nature's beauty confirmed Kohlhase as a staunch environmentalist. *Centurions*, above, showing hard-working oil pumps oblivious to the approaching storm, has been acquired by the World Meteorological Organization to dramatize fossil fuels' contribution to global climate change. *Siblings*, right, captures barn owl fledglings in the Eaton Canyon area of Pasadena. This nest had been used by alternating pairs of barn owls and great horned owls for many years until bulldozers returned to grade land for houses above nearby Kinneloa Mesa. The owls haven't been back since.

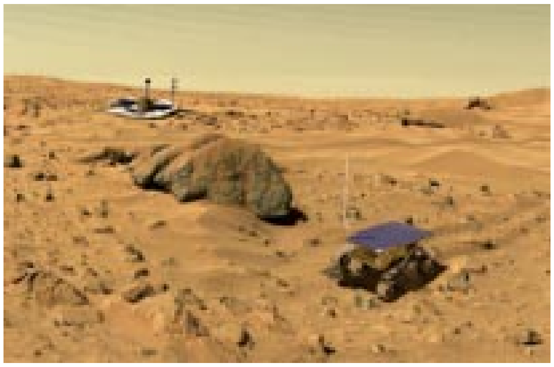


One outreach project remains in limbo—a 40-minute edutainment video following a photon named Dave as he leaves the sun, is absorbed and reemitted by Saturn's moon Iapetus, enters Cassini's Visual and Infrared Mapping Spectrometer, and gets encoded onto a radio wave for the journey back to Earth, where he winds up being reprocessed into an image on a young girl's computer. The sound track to *2004—A Light Knight's Odyssey* is finished. It stars the voices of John Travolta as Dave, and features, among others, Anne Archer, Sarah Michelle Geller, Samuel L. Jackson, James Earl Jones, and David Warner as the Void of Space. But the animation ran into financial problems, and the producer, Harry "Doc" Kloor, is trying to raise the funds to complete it.

In his spare time (such as it was), Kohlhase unwound by exploring the wild places of our own planet. "I logged 15,000 miles on one pair of Italian hiking boots over a 15-year period," he recalls. This became the inspiration for *Wilderness*, a pioneering computer game in which you were the sole survivor of a light-plane crash in the middle of nowhere. You got a topographic map and a few supplies salvaged from the wreck, and had to figure out where you were and find your way to a ranger station up to 90 miles away—the distance from Pasadena to Palm Springs. Assuming, of course, that you were clever enough to hike there in a straight line, as the game generated a landscape twice the size of Delaware.

Kohlhase and Wesley Huntress, then at JPL and now at the Carnegie Institution of Washington, invested some 3,000 hours in the game's creation over a two-year period. Kohlhase did the mission design, as it were, constructing the logic trees that drove the action (Is a bull moose seen? Do you ignore it? Does it charge? Are you hurt?) and writing the equations and procedures that modeled them. Huntress did the program design, scene graphics, and algorithm coding from the resulting four-inch-thick notebook. The game covered everything from jungle to scrub in all weathers, and even kept track of the motion of the sun and stars for navigational use. The duo drew on a U.S. Air Force survival manual, a medical doctor, a natural-history and wildlife expert, and the world's leading authority on toxic plants, among others, and *Wilderness* won high praise for its realism. It didn't make them rich, but it did win *Family Computing* magazine's Critic's Choice award for "text/graphics adventure" games in 1985 (yes, some games were text-only back then), and was rated among the top 10 educational programs by *Science '86*. Perhaps most telling, *Boy's Life* said that it "tests the cunning of even the most woods-wise outdoorsman." Says Kohlhase, "Even now, 17 years later, there's no comparable game on the market. We're considering a modern version, if any multimedia developers are interested."

Kohlhase got bitten by the shutter bug as a teenager, when he used to "borrow" his dad's darkroom



As computer technology grew to permit digital manipulation of photographs, Kohlhase kept up. The above view of Pathfinder on Mars was created in 1995—two years before the landing. The rover is a life-sized mockup at JPL. The lander is a six-inch toy Kohlhase shot in his back yard, using an old shirt for the deflated airbags. He Photoshopped them into a Viking image of a rock named Big Joe, adding the rover tracks and shadows. It's no wonder some people believe that the Apollo moon landings were shot on a sound stage in Burbank . . . *Dawn Patrol*, above right, is a more recent composite in which the Pacific Design Center has been turned on its side and the roof of a merry-go-round becomes a flying saucer. The other vehicles were computer-generated, and Kohlhase put himself in the driver's seat of the foreground one by way of signing the piece.

to develop and print his own work. He graduated to Kodachrome in college, and spent many years honing his technique on his innumerable hikes. Now he's a big fan of the new digital cameras, which give him a fast track to final prints without the darkroom chemicals.

Meanwhile, the collaborations with Blinn and Huntress led naturally to experimenting with Photoshop and the like as they came into being. "For someone who cannot draw or paint like the masters, computers are a godsend. Photoshop allows you to perform digital magic on any image you wish, and 3-D modeling and rendering programs let you create any scene you can imagine."

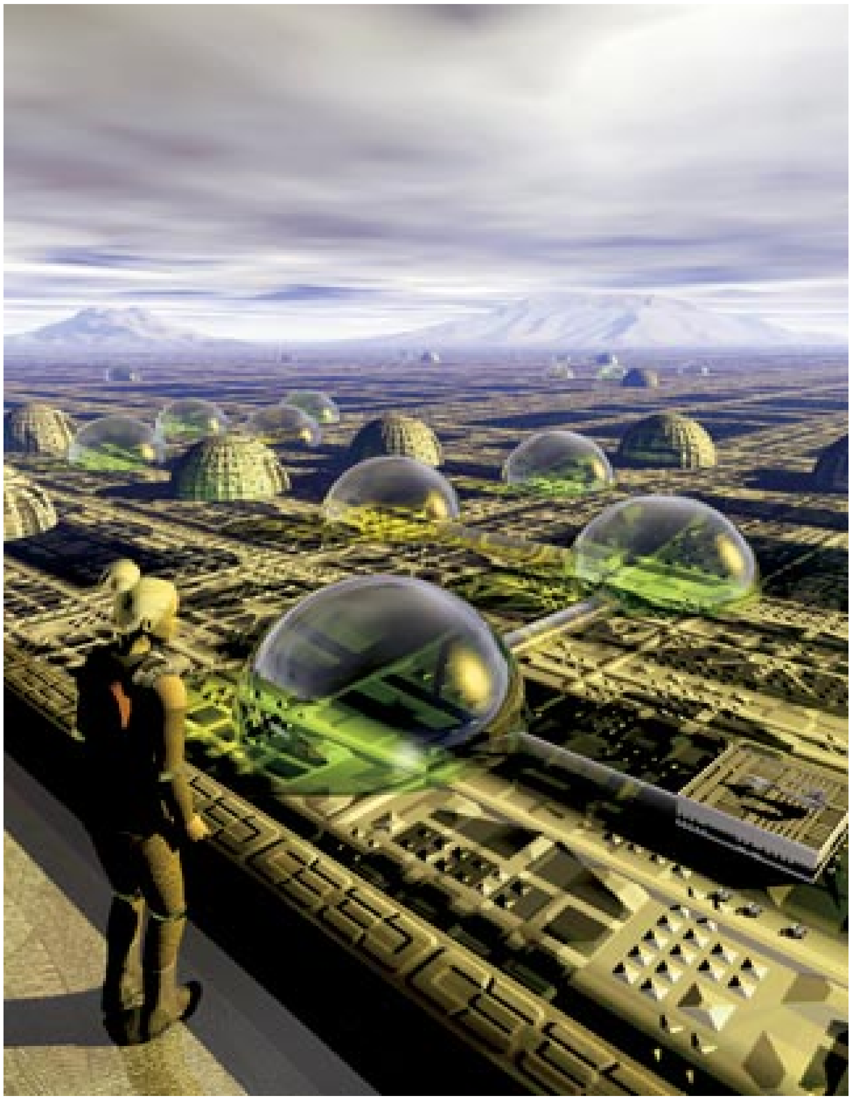
Kohlhase foresees artists using computers to create scenes beyond imagining through directed evolution. "Imagine taking the equations that govern the behavior of subatomic particles, atoms, molecules, DNA, cells, organisms, colonies, ecosystems, planetary systems, star systems, and galaxies. Immersed within this unfolding drama, you could guide its course at any scale and snap pictures with a virtual camera or save those 3-D models having irresistible appeal. Gulliver and the travelers of Jules Verne could not have beheld such sights." It's already beginning—for example, Eric Heller's images of an electron "gas" flowing in two dimensions over a bumpy surface are being sold as fine art. And Karl Sims has written software that generates three-dimensional animated abstractions that evolve as viewers in an art gallery select the most aesthetically pleasing ones and allow them to interbreed. Tom Ray has re-created Sim's software for the PC, so now anyone can grow their own.

Since science and art are both creative endeavors, and many people have a foot in both worlds, it's logical to ask what drives this creativity. Kohlhase did just that in 1999, when he came out of retirement to create the "Artists, Scientists, Engineers and Astronauts" portion of the "Mars Millennium Project" Web site, now the NASA/NEA/JPL

***Renee*, above, uses Photoshop's filters to achieve effects previously limited to 1970s album covers.**

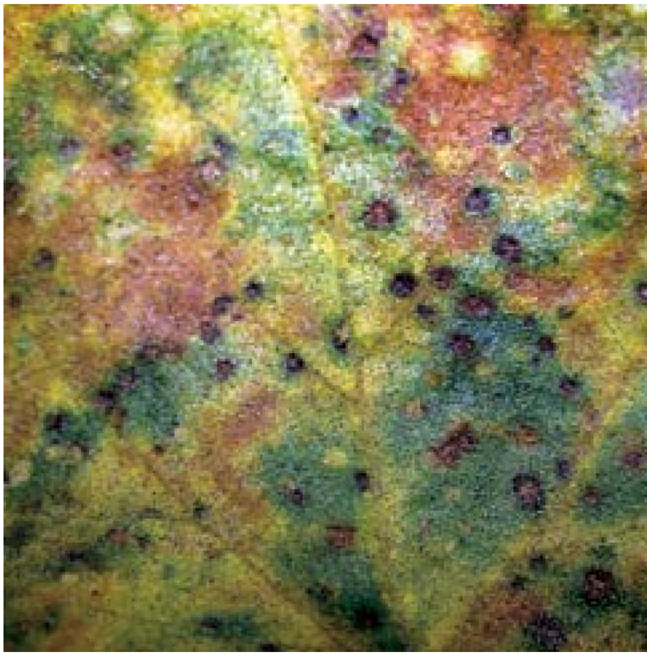
Eventually, of course, you don't need a camera at all. *Steel Sunflower*, right, was output directly from a 3-D modeling program. This is one of a series of "virtual sculptures" in brass and steel Kohlhase began in the mid-1990s—cutting-edge stuff at the time—and one of nine of his works selected by Joe Ruggiero (of *This Old House* and HGTV fame) for display at the Pacific Design Center's IdeaHouse in 1999–2000.

***Overlook 2135*, below, was the cover art for the December 2001 issue of *Creation Engine*. The image was rendered in a 3-D graphics package called Bryce, which is known for its realistic handling of landscapes and light. Kohlhase got bonus points for incorporating the magazine's CE logo into this cargo-storage facility at the nexus of several space-shipping lanes—note the top of the perimeter wall.**



"Imagine Mars" Web site (http://mmp.planetary.org). The site describes itself as "a national arts, science and technology initiative that challenges young people to imagine and design a livable Mars community of the future," and Kohlhase persuaded 72 people from 21 disciplines to contribute short essays on the essentials—cultural as well as technical—such a community would need. Each respondent answered three questions, of which only the last concerned Mars. The first two were, "How were you motivated to choose your particular field?" and, "What can you share about your creative process?"

Regardless of the chosen field, several common threads emerged. The two key attributes to unleashing creativity were preparation through education—a thorough grounding in the tools of the trade, be they math and physics for an astronomer, or countless hours of practice for a pianist—followed by the ability to stop and look at the "big picture" from all angles before plunging into the problem at hand. Of secondary importance was a cluster of four traits. One was relaxing after each bout of intensive concentration—the subconscious mind, unfettered, continues to work on the problem, and the solution will bubble to the surface unbidden during a jog through the park, or perhaps in the shower the next morning. (However, scientists were nearly twice as likely to say this as artists.) Another was bouncing ideas off colleagues inside or outside one's field—but not surprisingly, scientists were three times more likely to say this. The final two might really be one item that would thus rank as a third key attribute: "being happy in one's chosen field" and "being passionate about the work and jumping in with 'all burners on.'" To creative people, work is really play, and one's most productive periods occur when playful and self-disciplined states coexist and one effortlessly shifts between them as needed. At these times, says Kohlhase, people feel deeply alive, engaged, and oblivious to the passage of

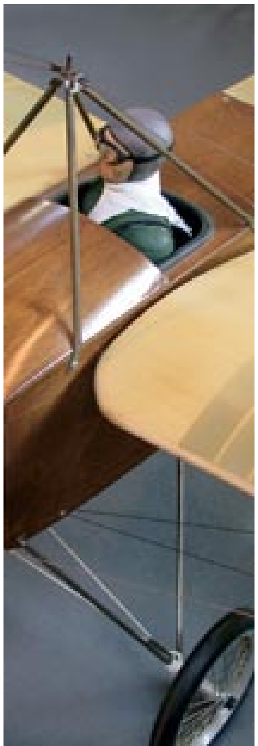


Serendipity and creativity favor the prepared—a shortcut under the Santa Monica pier during a walk on the beach resulted in the above image, which took all of 30 seconds to compose and shoot. Kohlhase has no idea what the two red boats were doing there.

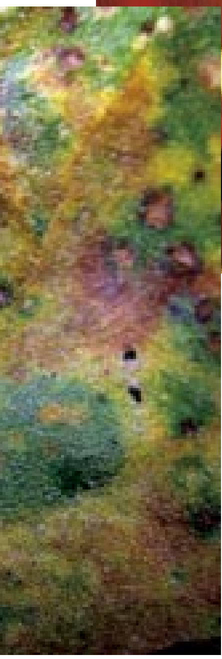
time. "The creative individual is playing with the balance of many forces—playfully energetic but good at relaxing, passionate yet objective, rebelliously independent but disciplined, and constantly moving between reality and fantasy. He or she is usually involved in more than one field, and aware of the great beauty of the natural world."

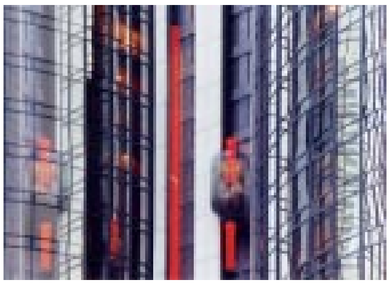
When asked what motivated their career choice, the most popular answer was the childhood influence of a parent, teacher, or friend who nurtured a talent or sparked an interest—anything from singing to watching an ant farm. Other reasons included storytelling in all its forms (including reading); exposure to the beauty of the natural world; and, for the scientists, innate curiosity and the thrill of the space age. Which was certainly true of young Charley—he built model airplanes and dreamed of flying, and his granny read him adventure stories. "I used to lie in the cool grass and gaze at the stars, but I would never have predicted this bounty. And I still get to watch my old Voyager companions try to reach the heliopause, while my newer Cassini–Huygens teammates seek the remote kingdoms of Saturn." □

Charles Kohlhase earned degrees in physics from Georgia Tech and in engineering from UCLA. He is a planetary mission designer, artist, author, educator, and environmentalist. Called JPL's premiere builder of missions by Spaceflight *magazine, he has received international acclaim for his 40-year body of work on Mariner, Viking, Voyager, and Cassini. He has recently returned to JPL part time to help with what he calls the "stunning queue" of upcoming Mars missions and as a technical advisor to the Kepler project to find Earth-sized planets orbiting other stars. This article was inspired by a Michelin seminar he gave on May 6, 2002.*

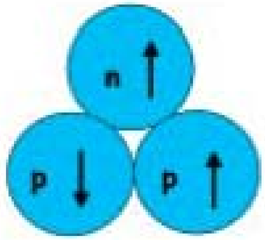


Kohlhase built the radio-controlled, quarter-scale model of a circa-1911 Bleriot at left from seven different kinds of wood. It took him 300 hours, so he's never had the nerve to fly it. (Over the years, he's crashed several models and lost a few more—including one that turned up five years later in a field 20 miles away.)





Nature is art, and reality is abstraction. It all depends on the scale of the view. *Presentation*, at left, is an array of oil and vinegar bottles at the farmers' market in Pasadena's Victory Park. *Nature as Art*, above left, is a half-inch portion of a tiny leaf. *Red Runner*, above top, is an exploration of the dimension of time instead of space—Kohlhase was shooting a long-exposure night scene in Amsterdam's red-light district when he was ambushed by the hookers' enforcer. He fled down the street with the aperture still open. *Urban Rider #2*, below it, is a piece of the Bonaventure Hotel in downtown Los Angeles—a geometric fugue of light, glass, and steel. And *Palette on Glass*, right, is a snippet of a 35-millimeter slide of a swath of coastal wildflowers near Big Sur, California, digitally enhanced with Photoshop's watercolor filter. For more images, see http://artshow.com/kohlhase.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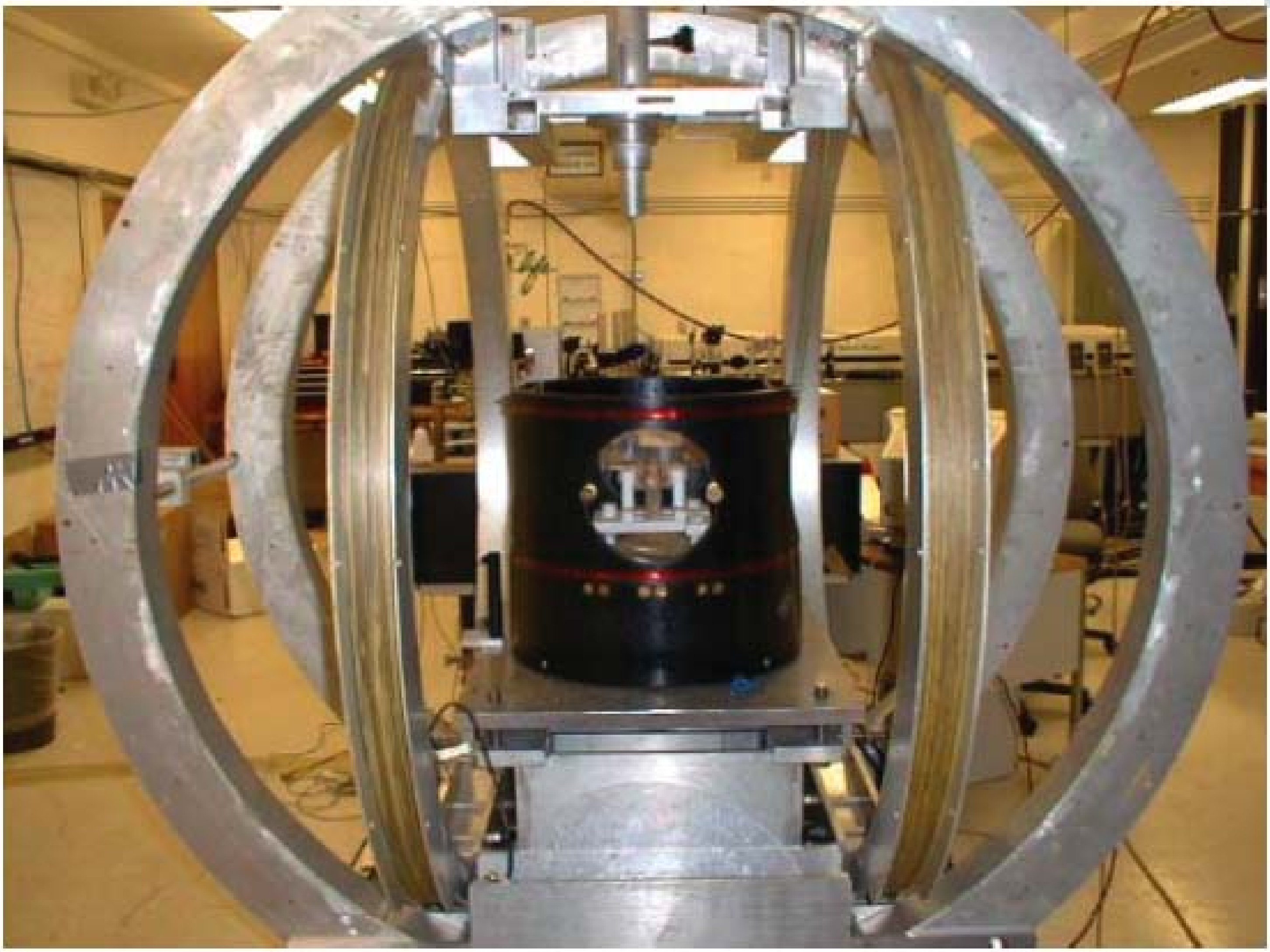
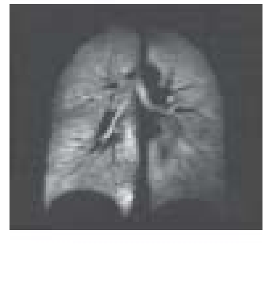




From High-Energy Physics to Medical Research . . . It Happens

by Emlyn Willard Hughes

Polarized ^{3}He (one neutron and two protons with opposite spins) has provided insights into the insides of a neutron and the insides of a human lung. In the neutron experiment at SLAC, about a liter of ^{3}He was polarized by high-powered lasers in the glass cell in the center of the target at left, which was then bombarded by electrons at energies of 50 billion electron volts. The steel coils surrounding the cell provide the magnetic field to control the spins. The target now leads a quieter life at Caltech, where it's dedicated to polarizing noble gases for medical imaging.

Research in fundamental science often spins off technological innovations. My story here is about an especially unusual spin-off, because it's so dramatically different from what we originally set out to do. I'm an experimental high-energy nuclear physicist, so first I'm going to torture you with a few details of our physics experiment, and then I'll go on to the spin-off, which landed us in biomedical engineering.

I'll start with the basics: the periodic table of the elements. If you survived as an undergraduate, certainly as one at Caltech, you battled with this in many different courses, and you probably know it in your sleep. You know its structure and how it all adds up. You know that electrons (and other particles) have spin and that Pauli's exclusion principle, which states that no two electrons with the same spin can occupy the same state, is the underpinning of the periodic table and explains the great variety in the structure of the elements. And you might know why the electron in a hydrogen atom doesn't collide with its proton, even though they are oppositely charged.

But even if you understand all of this, you probably cannot answer the simple, basic question underlying the periodic table: why does a proton stick to a proton? The protons are both positively charged, so certainly it isn't an electromagnetic interaction, but *something* is holding these two things together. A comparable question that is equally puzzling is, why does a proton stick to a neutron? These are reasonable questions if you want to understand the periodic table and how nuclei get to be nuclei. You might have smart kids who will come and ask you this someday. If you ask Caltech's provost, who is a nuclear physicist, you're going to hear things like field theory, the nuclear shell model, and other incredibly complicated stuff, but ultimately you will get the impression that perhaps we don't really know how to answer this question. That's why I spent 10 years of my life in nuclear physics trying to figure it out.

The first mental leap from those questions is this: if you want to understand how protons stick together, you probably should understand what's inside them and how the proton works. So let's look at what we know about the proton.

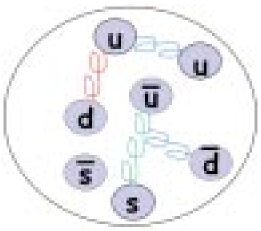
It's pretty simple in some ways. It has a charge of one and a spin of one half. We know that it has a mass of 938 million electron volts (MeV), and we know that it's a very stable particle. It has a lifetime much greater than the age of the universe—on the order of 10^{25} years, with even the most pessimistic measurements.

The neutron is very similar. It has a charge of zero and a spin of one half. It's a little bit heavier than the proton—939.6 MeV. One of the big differences between the proton and the neutron is its lifetime—a free neutron lasts only for about 15 minutes before decaying into a proton, an electron, and a neutrino. It's very stable when embedded in a nucleus, but it's difficult to study as a free neutron, because it won't stay around very long.

Our high-energy experiments to look inside these particles involved scattering an electron off either a proton or a neutron, so we had to create the proton and neutron targets. Now, proton targets are easy—you just use hydrogen (you can distinguish between the electron and proton in the scattering process). But for neutron targets, we had to use nuclei, because you can't produce a free-neutron target.

The proton, however, has a very complicated internal structure. We believe we understand *what* is inside the proton, but understanding its behavior is the difficult part. From the view of high-energy physics, the proton is not a fundamental particle. It's made up of smaller constituents—quarks and gluons—that we believe are fundamental, at least today. Quarks are the particles inside the proton, and gluons the mediators that cause the interaction between the quarks. It's complicated because the quarks come in different types, or "flavors"—up, down, anti-up, strange, charm, and so on. And the gluons aren't simple either; they have different "colors," and their interaction is a complex process as well. But this is what we've got to deal with if we want to understand how a proton works.

When you start trying to figure out something like this, you choose some particular question to answer. In the early 1990s, physicists had already looked quite a bit at what carries the mass of the proton and neutron, so the next question was: what carries the spin? Since protons and neutrons are made up of quarks and gluons, the problem became one of measuring how much quarks contribute to the spin versus how much of it comes from gluons. A somewhat crude measurement made at CERN (the European Organization for Nuclear Research) in Geneva found that the quark's contribution to the proton's spin was small. This launched experimental efforts all over the world to measure more precisely what the total quark contribution to the proton's spin would be. And this is where I came into it.



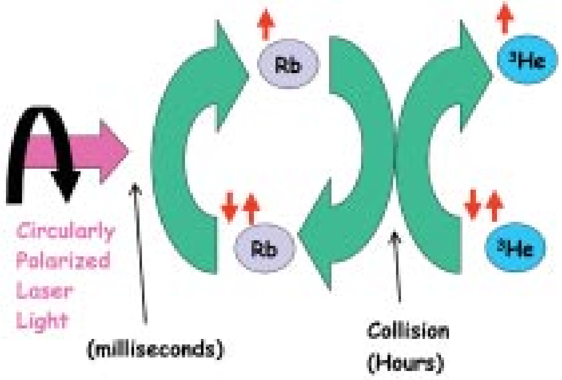
Above: Inside the proton are quarks that come in different "flavors"—up, down, anti-up, strange, and so on—and gluons, which mediate the interaction between the quarks and occur in different "colors." Below: The accelerator at the Stanford Linear Accelerator Center stretches for two miles, crossing Highway 280.

If you want to see inside the proton and neutron, you need to use a simpler particle like an electron, which we believe has no internal structure. You have to accelerate this electron to very high energies and then scatter it off the protons and neutrons, looking at the results in a detector. Because we wanted to understand something about spin, we had to do spin-dependent scattering. That meant that we had to control the spin of the electrons as well as the spin of the protons and neutrons. Our experiments scattered electrons with a particular spin off protons with a particular spin. The scattered electrons' spins were then parallel or antiparallel to the target's spin, and we performed an asymmetry measurement, counting the electrons we detected while keeping track of their spin.

To get the energies we want for our experiment, we need a very high-energy electron machine. We have one in Northern California—SLAC (the Stanford Linear Accelerator Center), which is two miles long and crosses underneath Highway 280 about half way between San Francisco and San Jose. SLAC produces electrons at energies of 50 billion electron volts and, at the end of the two mile run, flings them into a big experimental hall about the size of a football field, where we scatter them off various proton and neutron targets. The hall has to be huge because these collisions produce intense radiation, so all the equipment is heavily shielded.

For our neutron target at SLAC (remember, you have to use a nucleus, because free neutrons decay so fast that you might as well forget about controlling their spin), we used the nucleus embedded in polarized helium, specifically helium-3, or ^{3}He. Now, ^{3}He is just like ^{4}He: it doesn't decay radioactively, and it's a noble gas, which means it's inert and doesn't react with anything. The only difference is that ^{3}He has one less neutron. If you control, or polarize, the nuclear spins of ^{3}He, the two proton spins end up antiparallel to each other, due to the Pauli exclusion principle. These paired spins are effectively invisible, so if you scatter electrons off ^{3}He and you observe spin-dependent scattering, it has to have come from the neutron.

Our first problem was how to polarize the ^{3}He. We used a rather complex atomic physics method that basically consisted of mixing a bottle of ^{3}He with rubidium. If you heat up the rubidium, it produces a small amount of vapor, and you can use circularly polarized laser light to polarize rubidium atoms in the vapor. It takes a few milliseconds to polarize rubidium. Then, if the rubidium, which is now spin-up, collides with a spin-up helium atom, nothing happens. They both remain spin-up. But if this rubidium atom collides with a helium atom that's spin-down, then the two actually reverse spin, the rubidium



To polarize ^{3}He, you hit a rubidium atom with circularly polarized laser light, giving the atom spin up. When that atom collides with a spin-down helium atom, they reverse spin, but the rubidium immediately gets repolarized to spin up again and ready to change the spin of another helium atom. The first part of the process is very fast, but keeping it going long enough to obtain a liter of 50-percent polarized spin-up helium demands patience.

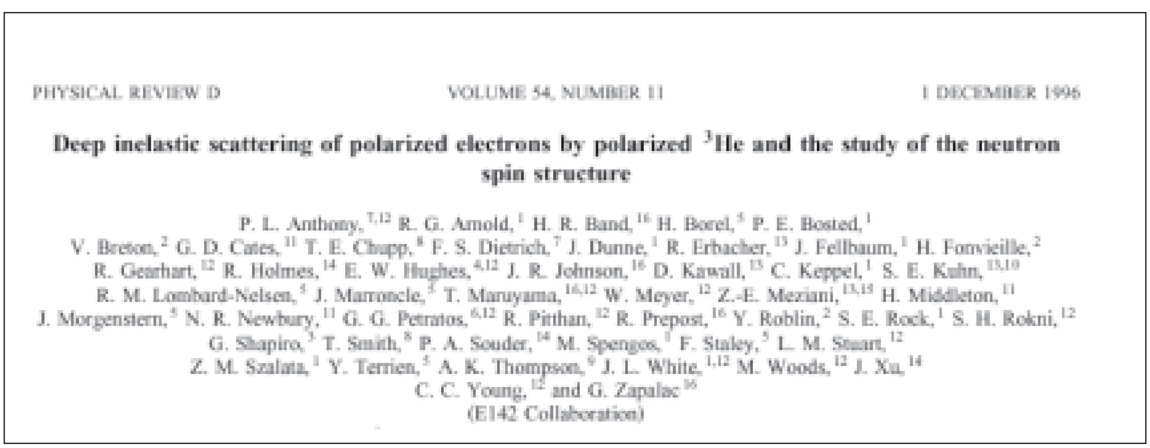
becoming spin-down and the helium spin-up. The spin-down rubidium quickly (milliseconds, again) gets repolarized by the laser, so, from the point of view of the ^{3}He atoms, they're always seeing spin-up rubidium. The ^{3}He-Rb interaction is weak; it takes hours to polarize the ^{3}He, but you can get to very high values—50-percent polarization—if you're patient enough to let it build up. We needed about a liter of ^{3}He for our target, which took 24 hours to polarize. Building it was a large, multimillion-dollar technical project, because it included all the equipment to polarize ^{3}He inside it. (When our experiment was over, SLAC didn't care about our target anymore, so I swiped it and brought it to Caltech, including all the polarizing lasers.)

I'll leave the experiment now and jump quickly to the results. We published a short paper in *Physical Review Letters* and later a longer article in *Physical Review D*, both with 48 authors. When you publish a high-energy physics experiment, you never get to see your first name; the most you can expect is your initials. You'll see the relevance of this later, when I move over to the medical side.

Over a 10-year period, start to finish, including building the target, we measured the quark contributions to the one-half spin of the neutron to be about 0.1—i.e., 20 percent of the spin, which is pretty small. We measured it to within an error of about ±0.05, which is quite a respectable level of accuracy.

We were not, however, able to measure the gluons very well. We found an upper limit on the gluon contribution to the spin of 1.7 ± 1. That's a gigantic error bar, so it's basically a non-measurement. We knew this going in, because the gluon measurement needs a much higher energy than SLAC can provide. You need to smash two beams head-on in a collider, because the center-of-mass energy is the sum of the energies in the two beams. In a fixed-target experiment like SLAC, you have only the energy from the electron beam. Such a collider does exist at DESY in Hamburg, Germany—a machine that can take a 900-billion-electron-volt proton and collide it with a 30-billion-electron-volt electron. But measuring the gluons is at least a decade away, because, although we know how to control the spin of the electron,

Embedded in the middle of a block of coauthors, "E.W. Hughes" hardly stands out. And there's only room for initials.


PHYSICAL REVIEW D VOLUME 54, NUMBER 11 1 DECEMBER 1996

Deep inelastic scattering of polarized electrons by polarized ^{3}He and the study of the neutron spin structure

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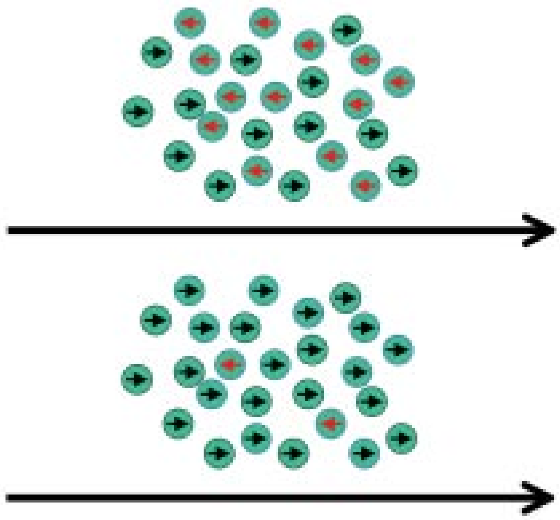


Atoms in a magnetic field (top) align their spins with or against the direction of the magnetic field (arrow). The signal in an MRI scan comes from the tiny excess of water atoms aligned with the field. Hyperpolarized noble gases (bottom) have a much larger percentage of atoms aligned with the field, which, even though the density of atoms is less, produces a larger signal.

we don't yet have the ability to produce a beam of polarized protons. So that's one problem with this field. U.S. scientists would like to build a somewhat lower-energy collider, but to really see the gluons, we need the highest energies possible.

A publication from a typical collider experiment today has about 500 authors' names on it—far more than even the publication from our SLAC experiment. It's amazing that you can still *see* the initials! And at an experiment at CERN, which is the next frontier in energy, the size of the collaboration would be approximately 1,000 names. This is just a fact of life in high-energy physics. So it was time to start looking for other things to do, especially with 10 years to wait, and that's how we got into the medical spin-off.

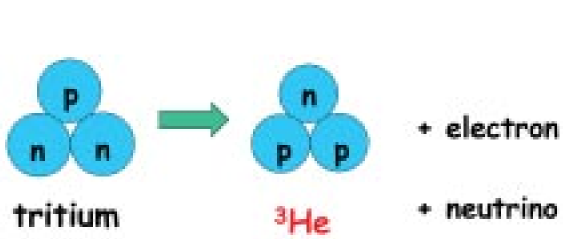
Before we did our SLAC experiment, it took lots of money and lots of work from a big team of atomic physicists to produce polarized ^{3}He. Before that, the most anyone had produced was about one cubic centimeter of it, so we had to figure out how to make the stuff by the liter. Some of the atomic physicists in our group, who weren't inclined to hang out very long in these large collaborations, realized very quickly that you can actually use this polarized gas for something else—magnetic resonance imaging (MRI, which also works on spin). First of all, a noble gas like helium (^{3}He is just like ^{4}He in this respect) is completely safe in the body. And the second important thing is that the high polarization gives you control over a large number of spins, so that you can produce very large signals. By combining the technology of MRI with this technology of polarizing a harmless gas that can be inhaled, the lungs could be imaged.

When you have an MRI scan, you put yourself inside a large, superconducting magnet with a very high magnetic field. The signal that makes the image comes from water inside the body. The spinning protons in the hydrogen nuclei act like tiny magnets and align their spins with or against the magnetic field. The higher the field, the greater the proportion of protons that line up with it, but the excess is very small even in a strong field—on the order of 10^{-4} (one in ten thousand)—and your signal strength is proportional to that number. The advantage of a water signal is that of density: you have lots of nuclei to look at, but you do have to go to extremely high magnetic fields to get a nice image, which is why we have to use these large MRI monsters.

But remember that we can make a noble gas with 50-percent polarization—a gain of four orders of magnitude. We lose density—there aren't so many nuclei to look at—but the polarization is so high that we can still get large signals. It's very hard to image the lungs with a conventional MRI scanner, because you get no signal at all from the air spaces, plus the water content of the lung tissue and the mucous membrane varies widely. But with this hyperpolarized ^{3}He, wherever the gas goes, you see a signal.

There is one little problem with ^{3}He: unlike ^{4}He, which is available everywhere, ^{3}He comes from weapons programs. So it's good to have access to a good weapons program if you want to do this type of research. I'm not going to get more political than that, but if you have lots of tritium, the price of ^{3}He goes down, and if you have a limited supply of tritium, which is used in nuclear bombs, it goes up. The price per bottle fluctuates from \$100 to \$300; it's supply and demand. Tritium, a radioactive isotope of hydrogen, consists of two neutrons and a proton. It decays into ^{3}He—two protons and a neutron—which is *not* radioactive but absolutely stable and safe.

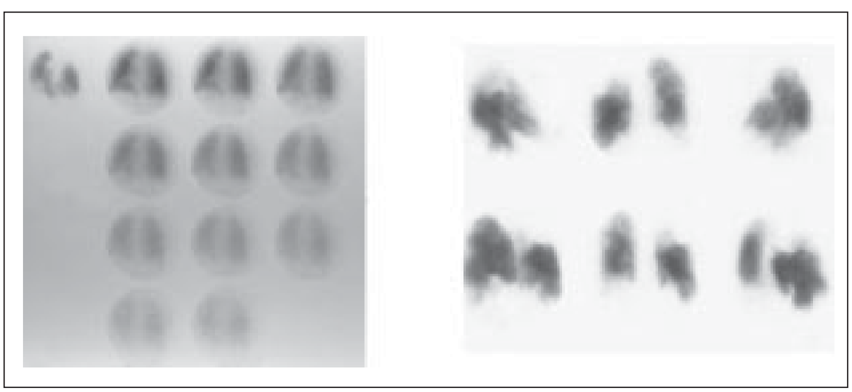
Now, it turns out that there's another noble gas that is of no interest to high-energy physicists but is interesting for doing medical imaging, and that's xenon. The isotope ^{129}Xe has just the right number of protons and neutrons added up, (meaning an even number of protons—54—so that they will pair off and cancel out, and an odd number of neutrons—75—so that there will be one left over to polarize), and it also has a spin of one-half. It's not radioactive, and like helium, it's safe to inhale. Helium, as you know, is used for balloons, and kids inhale it all the time—the only effect is that your voice gets very high. Xenon is used in bright flashlamps, and if you inhale xenon, your voice



Tritium, a radioactive isotope of hydrogen used in nuclear bombs, consists of two neutrons and a proton, which decay into two protons and a neutron: ^{3}He, plus a couple of other little things.

gets very low (which, you will remember from Physics 2 at Caltech, is because the speed of sound in gas is dependent on the mass of the gas nuclei).

^{129}Xe is much easier to obtain than ^{3}He; it's cheap and plentiful, and you don't need a weapons program. Xenon exists in the air at 87 parts per billion. It's very easy to separate xenon out of the air—something that can be done for about $10 a bottle. About 26 percent of xenon in air is ^{129}Xe, which is the spin one-half isotope that you need in order to see signals. The signal is diluted, because about three-quarters of the xenon is unpolarized. Although we can get much higher polarization for ^{3}He, it takes hours or days to achieve, as I mentioned earlier. You have to have high-powered lasers and be very patient. And, while our ability to polarize ^{129}Xe is limited (about 5 to 6 percent), it takes only tens of seconds to get to the maximum value. So there are two good possibilities for noble-gas imaging, each with different advantages and disadvantages.



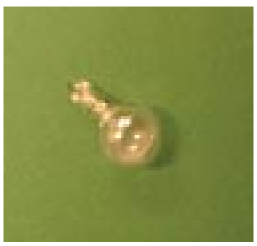
A breathing rat lung (top), as well as a human lung (right) were imaged using ^{3}He. (Rat lung courtesy of G. Allan Johnson and human lung courtesy of James MacFall, both of the Duke Center for In Vivo Microscopy, an NIH/NCRR National Resource.) These images are clearly far better than the V/Q scan of a human lung (below) currently used by doctors. (CAT scans can produce nice lung images, but only with high doses of radiation.)

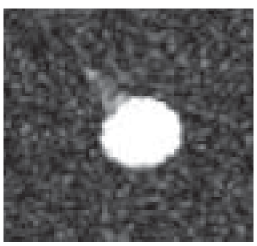
When we compare the magnetization of the signal of water (from a conventional MRI scan) to the signal of polarized ^{3}He, we find that they're roughly similar. Magnetization is roughly the magnetic moment times the density times the polarization, and the magnetic moment of water and ^{3}He are similar. The density of water in the body is, of course, much higher than that of an inhaled lungful of ^{3}He, but the polarization of the ^{3}He is much larger than the polarization of water. Multiplying these things together gives a ^{3}He signal that's roughly 10 times bigger than the water signal, but because there are details I'm leaving out, in the end they are comparable in size.

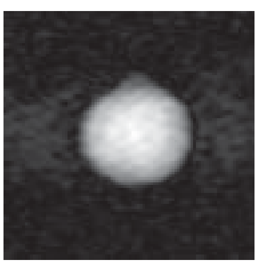
At left is a human lung image using polarized ^{3}He gas, made in the mid '90s at Duke University. The radiology department at Duke worked with our Princeton collaborators from the SLAC experiment to produce the polarized ^{3}He gas. You can see that it already makes a very nice image of the lung, and there have been improvements since then. The group also has made dynamic images of the lung of a breathing rat.

Compare this to the image at left, which represents the current lung-imaging technology. If doctors are worried about a possible blood clot in your pulmonary vessels, they'll give you a V/Q scan, which is a measurement of the ventilation of the lung and the perfusion. The perfusion is especially important, because that's what will tell you where the clot is or whether there is indeed a clot there. A radioactive dye is injected into the body, which shows up the structure of the lung, as seen in the right-hand set of images. At the same time, the doctor checks the ventilation to see where gas is going in the lungs, which is the left-hand set of images. You can see that the ventilation pictures have much worse resolution than the Duke group's image. The ventilation images were made by inhaling ^{133}Xe, which actually *is* radioactive. It's an FDA-approved procedure, and these

Left: The small (big enough for wrist or rat), low-field scanner in a Stanford electrical engineering building. Below it is a blown-glass cell of polarized xenon, and below that, the scanner's image of the cell. The Stanford scanner can also make images of a water cell (bottom).







scans are routine today, but I would much rather inhale spin-one-half, stable, nonradioactive ^{129}Xe than this stuff. So there should be no discussion about the safety of inhaling ^{129}Xe, and in the end you would also get a much better ventilation image.

Now I'll get to my own current research, which is a collaboration between Stanford and Caltech—"Stantech," we call it. (We decided that Calford didn't sound as snazzy.) Stanford is very powerful in magnetic resonance imaging, plus they have a medical school and a hospital, which gives them certain advantages, so I gave in to putting their name first in Stantech. Caltech has the experts in polarizing a noble gas, and you need both in order to do this type of research. My Princeton collaborators left physics five years ago to join the Duke radiologists, and I began getting into this field only over the last couple of years, so I needed a new gimmick. And Stanford has one: an electrical engineering group (particularly interested in cardiac imaging) is trying to develop low-field MRI techniques to compete with high-field techniques—and which will have a price tag a hundred times less per scanner. So we linked ourselves to the low-field imaging program at Stanford. From the atomic-physics point of view, we don't care at all what the magnetic field is. Using our polarized noble-gas technique at a low field (30 gauss) is just as effective as doing it at high field as far as we're concerned. There may even be some advantages as well, compared to high field.

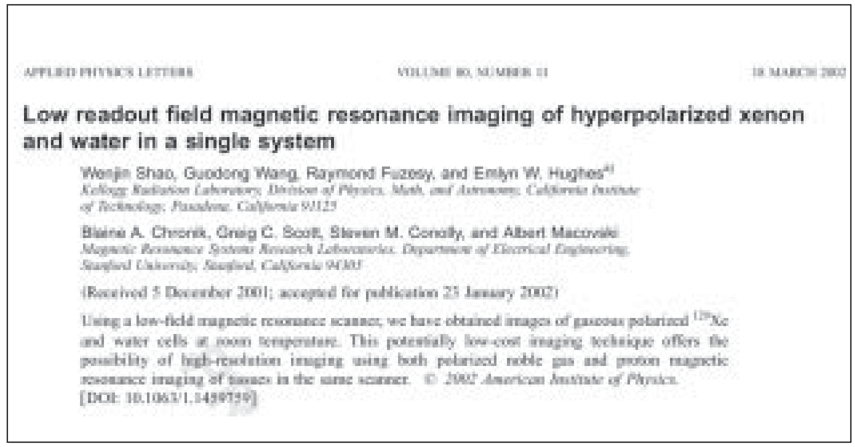
There's one minor problem: although the Stanford engineers collaborate with the medical school and all *their* scanners are located in the medical school, the low-field scanner that *we're* tied to is in the basement of an electrical engineering building that is not approved for animal imaging. So none of the images from our collaboration over the last year and a half are of animals. This is really unfortunate. We wrote a grant proposal to the American Heart Association last year that got rave reviews. The Stanford cardiologists supported us, but we got turned down because we said we wanted to image a dead animal; we figured, a dead animal, a rat, who cares? But it turns out you can't do that. Dead animals turn out to be just as politically sensitive as live ones. ("How did you get the dead animal? Did you kill it?") They picked up on this because of the scanner's location in the nonapproved electrical engineering building. We will resubmit that proposal next year and drop the rat comment. We can develop the technology without rats.

Xenon has several potentially useful properties. It dissolves in the blood and even keeps its polarization there for a few seconds. And because xenon is a large atom with a large nucleus, it has large chemical shifts relative to its environment. (Without going into details, this means that the radio frequency at which a xenon atom shows up in the scanner is very sensitive to that atom's chemical environment.) For example, it has been shown that nuclear magnetic resonance scanning of xenon in oxygenated, as opposed to deoxygenated, blood will cause a shift in the signal that can be separated out.

Now comes the caveat: it turns out that xenon is an anesthetic. If you inhale a lot of xenon, it does interact with the body, which ^{3}He doesn't. This has never stopped doctors from putting radioactive ^{133}Xe into people's lungs, but it does place limits on the amount you can inhale. (You can actually inhale quite a bit before you pass out, but it's officially a drug.)

We spent enormous effort on getting polarized ^{3}He working at SLAC in our high-energy experiments, and we're just getting started on ^{129}Xe. So we're looking closely at the atomic physics of xenon. From the atomic-physics point of view, the big problem is that at high densities, xenon depolarizes rubidium. Typically, we can polarize xenon at only about the 5 percent level versus 50

The author finally sees his first name in a publication with only seven others. (Albert Macovski, a renowned medical-imaging engineer, also held a patent, now long expired, for color TV.)


APPLIED PHYSICS LETTERS VOLUME 80, NUMBER 11 18 MARCH 2002

Low readout field magnetic resonance imaging of hyperpolarized xenon and water in a single system

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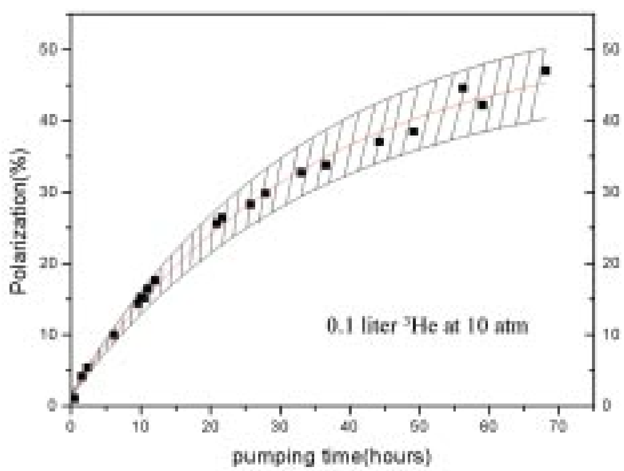
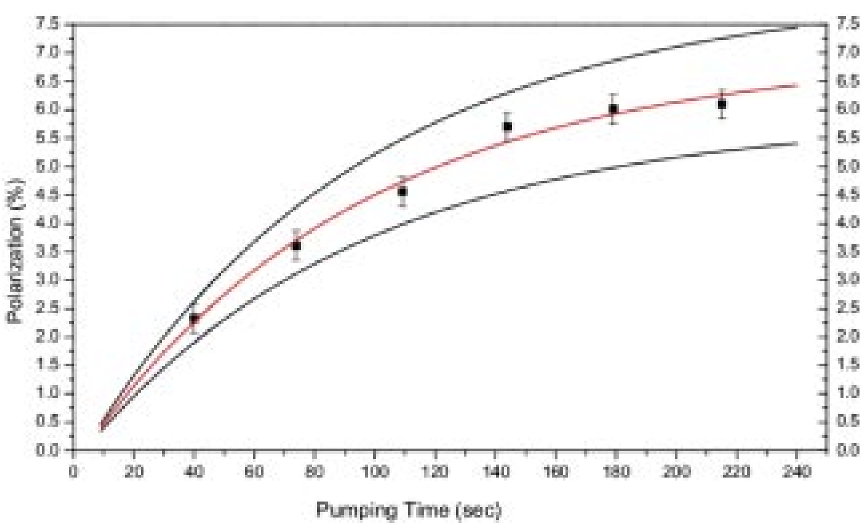
Using a low-field magnetic resonance scanner, we have obtained images of gaseous polarized ^{129}Xe and water cells at room temperature. This potentially low-cost imaging technique offers the possibility of high-resolution imaging using both polarized noble gas and proton magnetic resonance imaging of tissues in the same scanner. © 2002 American Institute of Physics. [DOI: 10.1063/1.1459759]





Recent work by Guodong Wang obtained a spin-up curve (top) for a liter of polarized ^3He of close to 50 percent—but with a pumping time of 70 hours. In contrast, Wenjin Shao's spin-up curve for ^{129}Xe (bottom) gets to only 6 percent, but in four minutes.

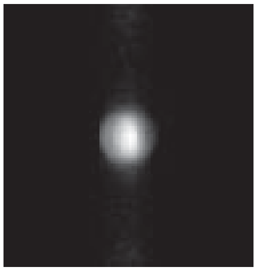
percent for ^3He, so the ^3He images are much better at the moment. My graduate students Wenjin Shao and Guodong Wang are trying to get the polarization of ^{129}Xe up to the 50 percent level, which will give us a 10-times-bigger signal.

We do the polarization studies at Caltech with the four big, fancy argon-ion Ti:sapphire lasers that I snagged from the SLAC experiment and brought home to my lab, but the simple imaging studies at Stanford require only a diode laser and a conventional magnet. We make a little cell of xenon, which we stick into the home-built Stanford low-field scanner. It has a small bore; you could image your wrist—or a rat. The center picture at the far left of the opposite page is an image of our xenon cell from the Stanford scanner. You can see that even with only 5 percent polarization, we get decent results.

Compare this to the nice resolution of the water image below it from the same low-field scanner. The Stanford group has focused for 10 years now on getting water images at low field that can compete with high-field ones. We are actually the only group in the world that can image both water and a hyperpolarized noble gas in a low-field scanner. (Harvard has a low-field project—even lower than ours—using a noble gas, but they can't get water images.)

The paper we published recently on the work has only eight authors—four from Stanford and four from Caltech. And my first name actually appears! For a high-energy nuclear physicist, that's really something to savor.

What are we planning for the future? We're continuing to work with both ^3He and ^{129}Xe. While imaging with xenon at Stanford, at Caltech we've also gone back to producing polarized ^3He cells to be used for imaging, as well as continuing to work on improving the xenon polarization. We're using our big laser system to study the detailed atomic physics of xenon with other alkalis besides rubidium, such as cesium and potassium.



Stantech's first image of a ^3He cell from the low-field scanner, made by Tina Pavlin last May.

You need an alkali metal, which has one electron in the outer shell, to make the process work.

Xenon has another advantage: it freezes at liquid-nitrogen temperatures, which extends the lifetime of the polarization to hundreds of hours. A group at Princeton has already done this. We haven't done it yet, but what's nice about this property for medical uses is that, in principle, we could produce polarized xenon in a lab at Caltech, freeze it, keep it in a magnetic field, and ship it all over the country to different imaging centers. If we can develop the technology to get a high enough polarization, we could in principle become a little "factory," producing the stuff, freezing it, and shipping it off.

We're also studying the diffusion times of ^{129}Xe and ^3He, which are quite different. ^3He diffuses very quickly. Now that can be very good, because it will diffuse into the lungs quickly. But for imaging you'd like it to stay in place once it gets there.

We're also looking at an advanced technique called spin-echo imaging, which is much quicker and could be important for functional imaging of the lung; and then, of course, we eventually hope to image animals and humans at Stanford. I expect that in the next year or two we'll be in that ball game.

Imaging techniques using polarized noble gases will be particularly handy for investigating asthma and cystic fibrosis (as well as chronic and obstructive pulmonary disease, emphysema, and lung transplant recipients), diseases in which it's important to look at how the lungs are functioning. It's not as likely to be helpful in lung cancer, although it's not out of the question that this type of imaging could see structural defects and nodules. We also think this sort of imaging will be especially applicable for children. You can actually get beautiful lung images with CT scans, but parents don't want to put their children in CT scanners because of the high radiation doses. MRI with a noble gas doesn't have any of the safety problems of CT scans.

In summary, research into polarized noble gases has broad applications, and until the high-energy physicists figure out how to produce polarized protons in an electron-proton collider, the fundamental physics research just has to wait. □

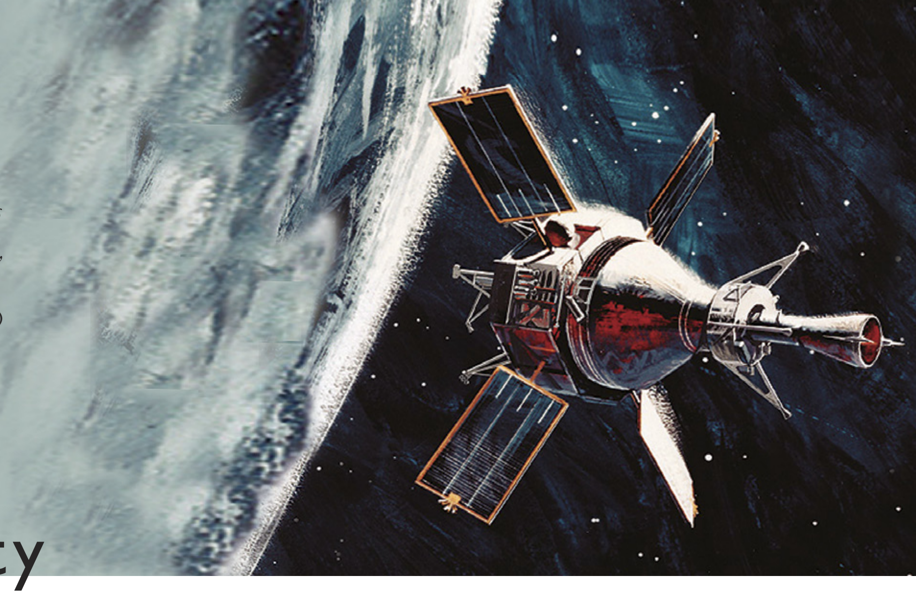
Emlyn Hughes, whose Seminar Day talk was adapted for this article (which lists his whole *name as author), has been professor of physics at Caltech since 1999. He received his BS from Stanford in 1982 and his MA (1984), M.Phil. (1985), and PhD (1987), all in physics, from Columbia. In 1989, he returned to the West Coast to the Stanford Linear Accelerator Center, where he was a research associate from 1989 to 1992 and a Panofsky Fellow from 1992 to 1995. In that year he arrived at Caltech as an associate professor. Hughes was awarded a Sloan Fellowship and an ASCIT Teaching Award in 1997; in 1999 he won the Feynman Prize for Excellence in Teaching.*

PICTURE CREDITS:
28, 30, 31, 32 – Emlyn Hughes; 30 – SLAC;
34 – Steve Conolly;
35 – Georgia Frueh;
37 – Lockheed Martin

The Caltech segment of "Stantech" includes, from left: grad students Wenjin Shao, who is working with xenon; Guodong Wang, who is focusing on ^3He; and Tina Pavlin (fourth from left), who works with the imaging group at Stanford; Emlyn Hughes (behind Pavlin); and two technicians, glassblower Faye Witharm and lead technician Ray Fuzesy, a "technical wizard" who worked for 30 years at Lawrence Berkeley Laboratory in the lab of Owen Chamberlain, who won the Nobel Prize for discovering the antiproton.

"Ptolemy invented a universe and it lasted two thousand years.
Newton invented a universe and it lasted two hundred years.
Now Dr. Einstein has invented a new universe and no one knows
how long this one is going to last."

George Bernard Shaw (1930)



A Touch of Gravity

by Eino-Ville Talvala

Once again, we present one of the best papers to come out of this year's Core 1 Science Writing course. The course is a requirement for all students, to help them improve their writing style and gain experience in communicating science to the general public (Alan Alda would approve). We'll feature another paper in our next issue.

Above: Illustration of Gravity Probe B in polar orbit. The satellite was built around the dewar, a thermos-like container full of liquid helium that holds the main instrumentation.

Chilling cold will surround translucent quartz spheres spinning silently in almost total isolation. Only the faint whispers of electric forces, and the ghostly touch of gravity, will reach into the cold vault of whirling gyroscopes. And, for a year and a half, they will spin ceaselessly while expectant scientists on Earth eagerly study the readouts of information streaming from the satellite orbiting far above them.

That satellite, called Gravity Probe B, carrying in its frigid interior some of the most precise measuring devices ever built, is currently in the final stages of construction at Stanford University and Lockheed Martin, with NASA providing funding and launch support. After more than 40 years of planning and building, it is now nearly ready, and is aimed to launch in April 2003. Its tale is deeply intertwined both with the discoveries in physics during the 20th century, and with the current efforts of physicists who are seeking the elusive "Theory of Everything."

The general theory of relativity, first put forward by Albert Einstein in 1916, overthrew Newton's law of gravity, which had been unable to predict accurately many of the observed phenomena that general relativity handles with grace. Einstein's theory, elegant in form (though often complex to apply), is one of the greatest theories ever conceived, and is his most powerful creation. It is also wrong.

General relativity and quantum mechanics, the two great theories of the 20th century, are fundamentally incompatible in structure. To reconcile the two, at least an amendment to general relativity is needed, or, as seems more likely now, a completely new theory must be created to explain the universe as we know it. Almost since the birth of these two theories, physicists everywhere have been seeking a Theory of Everything, also known as the Grand Unified Theory, which would combine quantum mechanics and general relativity into a theory that can describe all the interactions in the universe. This quest consumed Einstein's later life, but he never succeeded. So far, no one else has either.

But work has progressed, and today there are several candidates vying for the mantle of the Grand Unified Theory, many of them radically different from general relativity. And this is where Gravity Probe B steps in. (Gravity Probe A was a relativity experiment relating to the equivalence of gravitational and inertial mass, performed in 1976 by NASA and the Smithsonian Astrophysical Observatory.)

While many tests have been performed to verify general relativity, some of its predicted effects are almost too minuscule to observe. One such effect is called "frame dragging," and it is this effect that Gravity Probe B will measure. Frame dragging is a phenomenon that is created by massive spinning objects such as stars or, to a lesser extent, planets like Earth. Just as a heavy marble that is pressed against a tablecloth and spun will twist the tablecloth around itself, the spinning of Earth drags space-time, twisting it in the direction of Earth's spin. This effect has never been measured, because it is vanishingly small. The measurable effect of frame dragging is to twist the axis of rotation of a spinning object near Earth slightly over time, with the predicted magnitude of the effect being roughly 42 milliarc-seconds per year. (A single milliarc-second is equal to the apparent width of a lone human hair, as seen from 10 miles away.)

Gravity Probe B will contain four gyroscopes, the most accurate ones ever made. Once they are in orbit, they will be capable of detecting changes in their axes of rotation of 0.1 milliarc-seconds, a feat that cannot be equaled in ground-based experiments. Only in the microgravity of spaceflight can the gyroscopes spin without needing physical support—support that would destroy any hope of achieving the necessary accuracy, because of the mechanical vibrations and friction it would cause. The gyroscopes will be shielded from all

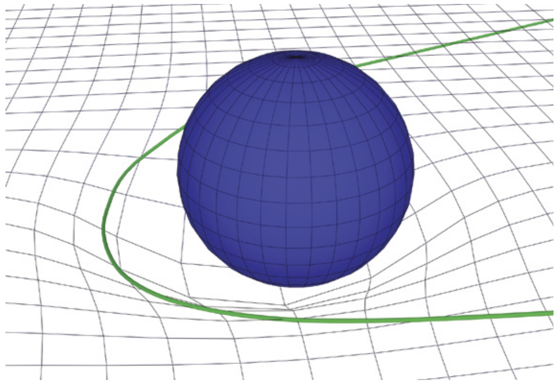
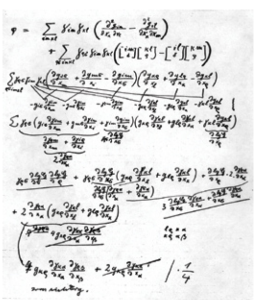


Illustration of curved space-time around a massive object. The green curve is the trajectory of a smaller mass that is deflected by the space-time curvature created by the heavy object.

external forces (such as solar wind, magnetic fields, and micrometeors) that could conceivably disturb them in the slightest and thus erase the faint traces of the frame-dragging effect.

With the measurement of the frame-dragging effect that Gravity Probe B will provide, any candidate Grand Unified Theory that predicts other values will be ruled out; if no frame-dragging effect is found, almost all the current theories will be shown to be lacking. Either way, the results will further the search for the ultimate goal of physics—the Theory of Everything. As stated at Gravity Probe B's project Web site (http://einstein.stanford.edu): "If we better understand the nature of mass and space, we may be able to do things previously undreamed of. So far, studies of relativity have yielded atomic clocks, guidance systems for spacecraft, and the Global Positioning System. We are limited only by our own imaginations when it comes to applications of science. Who knows? Maybe we can someday learn to manipulate gravity as thoroughly as we now manipulate electricity. We cannot foresee all that may come from a better understanding of space-time and mass-energy, but a theorem about these fundamental subjects must be thoroughly examined if we are to use it to our advantage."



A page of Einstein's research notes showing his efforts to develop the curvature scalar (ϕ at top left) for the general theory of relativity. From the third line down, he expands out only the first term on the second line. (Page 234, vol. 4, *The Collected Papers of Albert Einstein*; courtesy of The Albert Einstein Archives, the Hebrew University of Jerusalem.)

Into the past—the history of relativity

To understand the goals and significance of Gravity Probe B, a brief dip into the history of physics is in order. In the late 19th century, the laws of physics were thought to be nearly complete in their ability to explain the material world. Isaac Newton had described gravity 200 years earlier; James Maxwell had explained the phenomena of electricity and magnetism with his equations in 1873. Except for studies of a few minor unexplained phenomena, which were expected to be mopped up in a few years, it seemed to many that theoretical physicists would soon be out of a job. But this fate was not to be.

The problematic issues, such as the infinite values that arose in calculations of the energy output of an ideal heat-emitting object (a "blackbody"), and the stubborn undetectability of something called "the ether" (a medium that was thought to carry all light waves, as sound is carried by air), could not be easily resolved, and eventually resulted in a complete rewrite of the laws of physics.

In 1905, the first rewrite saw the light of day, as Einstein (with contributions from prominent scientists of the time such as Hendrik Lorentz and Jules-Henri Poincaré) published work that established the initial expression of the special theory of relativity. The theory did away with the ether, established the speed of light as the universal speed limit for mass and energy, and laid out his now-famous $E = mc^2$ equation. The theory was subsequently accepted by the scientific community, but soon a significant problem arose.

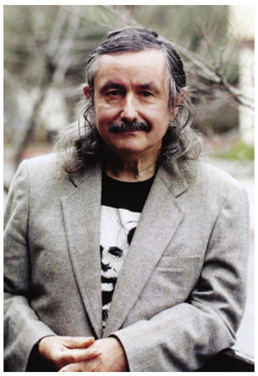
Special relativity contradicts Newton's law of gravity. According to Newton's law, the force of gravity acts instantaneously; if Earth were to become heavier in an instant, Newton predicted that everything in the solar system would feel the effect of this change in the same instant. This instantaneous response conflicts with special relativity's restriction that nothing can travel faster than light. Einstein immediately set out to resolve this conflict.

In 1916 he succeeded, publishing his general theory of relativity. According to Newton's laws, space was merely a backdrop upon which physics happened. In Einstein's view of the universe, space and time are active participants in the workings of physics. Whereas Newton described gravity as a force field that was created by all mass, Einstein saw gravity as the curvature of space-time itself: Mass tells space how to curve, and space tells mass how to move, as Princeton's John Wheeler put it. The diagram above left gives an idea of how this can happen.

To physicists, general relativity is conceptually simple and relies on only a few basic postulates and theorems. However, the mathematical framework for the theory consists of 10 "coupled hyperbolic-elliptic nonlinear partial differential equations," which take up several pages in their fully expanded form, and are likely to give any mathematician (not to mention everyone else) a severe headache. (Even Einstein found it difficult, see right.) However, when physicists are dealing with the effects of gravity sources that are weak (such as Earth, or just about anything less dense than a neutron star), the theory can be approximated into a simpler form. In this simpler form, a more intuitive description of frame dragging can be found.

The simpler equations look like those for electromagnetism. Electromagnetism describes electric and magnetic fields; with the simplified gravity equations, analogous "gravitomagnetic" and "gravitoelectric" fields can be derived from the overall gravity field. The gravitomagnetic field is created by moving masses, much as magnetic fields are created by moving electric charges. This field, created by Earth's spin, will interact with the spins of Gravity Probe B's gyroscopes, creating the frame-dragging effect (also known as the Lense-Thirring effect, named for the physicists who first isolated the effect from Einstein's equations).

Testing history



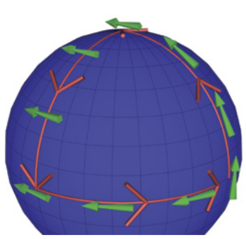
Francis Everitt, principal investigator for the Gravity Probe B project.

Gravity Probe B is intended to measure the frame-dragging effect to an accuracy of 0.3 percent, and will be the first direct measurement of the effect and of its magnitude. While many scientists feel confident that the results from Gravity Probe B will simply confirm Einstein's predictions, there are those who expect that the answer will be something quite different. As Nobel laureate Chen Ning Yang put it: "Einstein's general relativity theory, though profoundly beautiful, is likely to be amended . . . The Stanford experiment is especially interesting in that it focuses on the spin. I would not be surprised at all if it gives a result in disagreement with Einstein's theory."

Gravity Probe B is also measuring a second effect of general relativity, though this is one that has already been investigated. This "geodetic effect" is a much larger force than the frame-dragging effect. The geodetic effect is the sum of effects from two sources: Earth's gravitoelectric field, and the curvature of space-time around Earth itself.

Four-dimensional curvature of this type is hard to visualize, but the simplified analogy below can help explain its contribution to the geodetic effect. The combined effect of these two phenomena should result in a turn in the axis of the gyroscope's rotation of roughly 6 arc-seconds per year, a change of over 100 times that of the frame-dragging effect.

While the geodetic effect has been measured before by lunar laser-ranging experiments, Gravity Probe B will measure the effect to a precision of 75 parts per million (which is like measuring room temperature to three decimal places), which will be a vast improvement over previous measurements.



The red line follows a round trip made on a curved surface by a traveler holding a gyroscope. On returning to the starting point, the spin axis of the gyroscope (green arrow) would have turned 90 degrees from its original heading. Similarly, a satellite orbiting Earth travels through the curved space-time around it and, with each orbit, the orientation of the satellite changes slightly.

Combined, the two measurements that Gravity Probe B will make will probe the characteristics of spinning massive objects more deeply than any previous experiment, and give physicists new insights into the Grand Unified Theory.

The satellite itself

Gravity Probe B was envisioned in 1960 by three scientists working at Stanford University: Leonard Schiff and William Fairbank of the department of physics, and Robert Cannon of the department of aeronautics and astronautics. Together, they started a development group that, since 1962, has been led by Professor Francis Everitt (left), the principal investigator in charge of Gravity Probe B.

Because many of the requisite technologies did not exist at the start of the project, over the years the Gravity Probe B group has by necessity furthered the state of the art in dozens of fields. The group has realized large gains in cryogenics, gyroscope construction, and superconductor research. For example, a graduate student in the Gravity Probe B group developed a dewar that can be used to store the liquid helium the probe will need in orbit. This device has already been used in other satellites that need extreme cooling, such as the COBE satellite that first mapped the cosmic microwave background radiation.

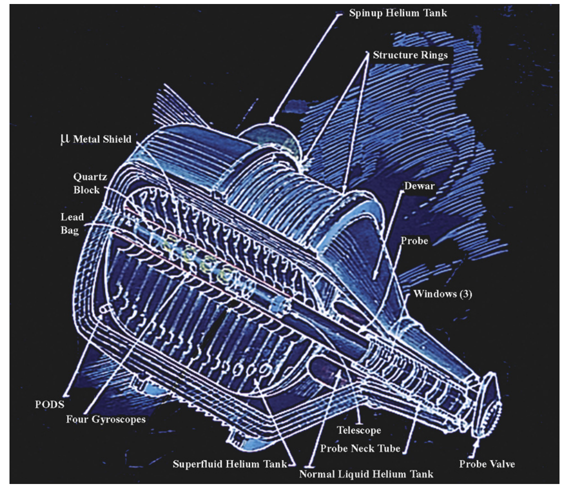
There will only be one chance for the Gravity Probe B experiment to succeed, so the project has been studied over and over again, and every effort has been made to find any and all sources that might cause trouble. Numerous reviews by NASA, independent boards, and internal review groups have yet to find a detail that is not accounted for, a testament to the rigorousness of the planning for the project.

Beyond the technical challenges, Gravity Probe B has faced significant political obstacles. Due to the length of the project, it has often faced congressional scrutiny and budget-cut threats. It probably helps in his dealings with Congress that Professor Everitt looks very much a physicist in the style of Einstein; he even has a similar hairstyle.

So, after all this work and planning, what is the satellite like? The main structural element is the liquid-helium dewar, capable of holding 400 gallons of helium. (A dewar is a cryogenic container for storing very-low-temperature liquids and materials. Essentially, it is a large, complex thermos bottle.) The dewar contains the main science probe; this includes the gyroscopes, their readout systems, and the reference star-tracking telescope, which keeps the satellite oriented toward a guide star. The rest of the spacecraft is built around the dewar. This includes solar panels, control thrusters, and the computer systems.

In order for Gravity Probe B to work, the gyroscopes need to be shielded from all possible

A cross section of the liquid-helium dewar. Gravity Probe B carries four gyroscopes, placed along the spin axis of the satellite with high precision, and surrounded by lead bags to remove magnetic fields. The star-tracking telescope sits at the top of the main quartz block, looking out through transparent windows in the dewar's neck. The liquid helium is used for cooling and as a reaction mass for attitude control. © Barron Storey.



external forces besides gravity. This has required many ingenious design methods to eliminate outside influences on the gyros, and is the main source of complexity in the probe's design. The most important parameters that must be achieved by Gravity Probe B have been dubbed the Seven Near Zeros:

1. **Low temperature.** Liquid helium will cool the gyroscopes to 1.8 kelvins (–457.2 degrees Fahrenheit).
2. **Low pressure.** The gyroscope structure is surrounded by a cylindrical shell kept at a vacuum emptier than space (10^{-11} torr, or one hundred-trillionth of Earth's sea-level pressure).
3. **Low magnetic field.** Various shields will reduce the magnetic field inside the dewar to one ten-millionth of Earth's magnetic field (10^{-7} gauss).
4. **Low gravity.** Achieved by testing in space.
5. **Low density variation.** The gyroscopes are made of very uniform quartz to make them spin without any aberration.
6. **Near-perfect sphericity.** The gyroscopes are perfect spheres to 40 atomic layers, covered by a uniform layer of metal.
7. **Near-perfect electric sphericity.** The surface properties of the gyroscope remove any irregularity in the electric charge of the gyroscope.

A completed gyro rotor, the size of a ping-pong ball, and its housing.

The gyroscopes must be held at such low temperatures to maintain superconductivity, on which the gyroscope readout and magnetic shielding rely. Liquid helium will boil off constantly through a special porous plug in the dewar to maintain the science probe at its required temperature for up to 18 months. The boiled-off helium will also be recycled to be used in the precision-controlled thrusters for the satellite, allowing very fine adjustments to be made to the satellite's orientation to track the guide star exactly.

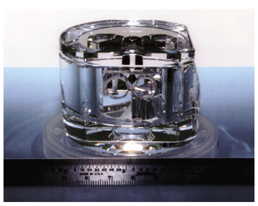
Because external magnetic fields (like Earth's field) destroy the accuracy of the gyroscopes' readouts, the probe's innards must be well insulated. This insulation is achieved with superconductors, materials that have no electrical resistance once they have cooled below a critical temperature, and that have properties that are very unusual. For one, a superconductor does not allow magnetic fields to pass through it. A hollow superconductor, therefore, will trap any magnetic field inside it permanently as soon as it becomes superconductive. In Gravity Probe B, superconducting lead bags are used to trap magnetic fields like this. The bags will be layered over the gyroscope housings, one on top of the next. They will then be expanded one by one, stretching the magnetic field trapped inside thinner and thinner, like a cook spreading out a lump of pizza dough.

The gyroscopes, consisting of a spinning rotor and the surrounding housing (bottom left), are triumphs of precision manufacturing: the rotors are smooth to within 40 atomic layers and are made of incredibly uniform fused quartz. Unlike, say, a pure metal sphere, quartz will not expand or contract with temperature (in contrast, small gaps must be left between lengths of metal railroad tracks because they are known to stretch on hot days); and quartz can be made to be very uniform in density, an important factor in making the gyroscopes spin without wobble. The gyroscope rotors, which will be secured to their housing during take-off, will free-float once the satellite is in orbit, and will never touch their housing after they have reached their operational speed of 10,000 rpm. The spin-up will be done by shooting supersonic helium gas past the gyroscope rotors, and will bring the gyros up to speed without harsh physical contact.

The experiment must also account for problems like the solar wind, which, even with its feeble push, could destroy the accuracy of the measurements. Therefore, the satellite is designed to track one of the gyroscope rotors, allowed to float freely in its cavity in the center of the satellite; the satellite will adjust its own orbit to keep the rotor centered in its housing, instead of exerting force on the rotor. Since the gyroscope is deep within the satellite, it will be protected from the solar wind, micrometeors, and similar phenomena. The rotor will therefore trace a near-perfect orbit around Earth, and the satellite will follow along with it.

The gyroscope design has also had to answer one of the original paradoxes of the Gravity Probe B project: How can scientists measure the orientation of a gyro that they cannot touch? Because any physical contact with a spinning gyroscope rotor would destroy the required accuracy, some way to read the position of the gyroscope was needed that did not interfere with the gyroscope itself.

In the end, the answer depends on another property of superconductivity, discovered by Fritz London. A spinning superconductor acts like a very weak magnet, with the poles of the magnet precisely aligned with the axis of the spin. The gyroscope rotors are covered with a layer of niobium, a metal that will superconduct when it is cooled by liquid helium. Therefore, a precise, but very weak, magnetic pointer will be created that will allow scientists to determine the spin axis of the gyroscope. Incredibly sensitive magnetometers, called SQUIDs, for Superconducting QUantum Interference Devices, will utilize other superconductivity principles to detect the faint fields from the gyroscope rotors, and to transmit this information to the flight computers.



This tiny star-tracking telescope made of fused quartz is only 14 inches long, with a 5.6-inch-diameter primary mirror, but the ingeniously folded Cassegrain optics give it a focal length of 12 feet 6 inches.

The metal layer will also help to keep the gyroscopes centered in their housings. Three electrodes in the gyroscope housing can exert electric forces to support the rotor during spin-up, or in case a micrometeorite impacts on the satellite.

From the precise SQUID information, the scientists on Earth will be able to tell how the gyroscopes are oriented relative to the Gravity Probe B satellite. However, this won't do much good unless they also know how the satellite is oriented relative to the rest of the universe; otherwise, there will be no way to know how the gyroscopes have moved relative to Earth's gravitational field. To establish its orientation, the satellite will point toward a guide star, using a very precise star-tracking telescope, above left. The guide star's motion is well known, and can be compared to faraway galaxies and quasars, which provide a fixed reference frame for the experiment.

The accuracy of the telescope must match the accuracy of the gyroscopes, so the telescope must be able to find the star with an error of, at most, 0.1 milliarc-seconds. From Earth, the chosen guide star (which is known in star catalogs as HR8703) has an apparent width of about 90 milliarc-seconds, so the telescope must do more than just point toward the star, it must find the center of the star to great accuracy.

The telescope, its supports, and the rest of the instrumentation inside the dewar, are made of quartz. New techniques to attach quartz to quartz were developed in the construction of the probe, including fusing separate blocks together so seamlessly that they look like they were carved from a single block. The resulting telescope is a thousand times more accurate than typical star-tracking telescopes, due in large part to the amazing stability of the fused quartz.

As of this writing, the heart of Gravity Probe B has been completed; everything inside the dewar is in place, and it has been cooled to operating temperature. Work is progressing on attaching the outer systems to the dewar and on verifying that everything works. So far, it looks good.

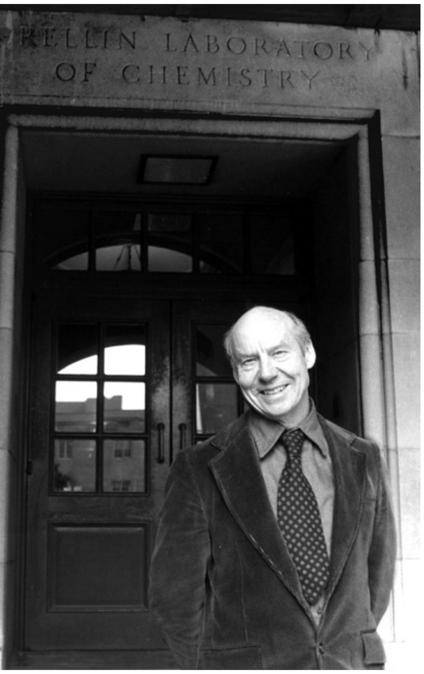
Toward the future

Gravity Probe B has a chance to either further confirm or, in one swift stroke, disprove general relativity, Einstein's greatest work. While physicists know that the theory must be amended, nobody has yet made a direct physical measurement that disagrees with general relativity. A measured value of the frame-dragging effect, and a very precise measurement of the geodetic effect, will one way or another rule out many possible Theories of Everything. While all theories, of course, must predict results that would be nearly identical to those of general relativity, the effects of spinning objects are an area in which the theories often disagree. Nothing helps out a theory more than a new measurement that agrees with a value the theory has predicted beforehand.

It is ironic that, in the end, measurements made from small spinning balls, isolated only with great ingenuity from the forces of the rest of the cosmos, will help uncover the underlying laws and structure of the entire universe. But until Gravity Probe B launches and spins up its gyros, the universe will be able to hide one of its great secrets for a bit longer. After so many years of work, Gravity Probe B has the patience to wait. □

Eino-Ville (Eddy) Talvala, a senior majoring in electrical engineering, has more than just an academic interest in Gravity Probe B: he's been helping to develop one of its subsystems during his summer breaks. This is his third summer at Stanford, but it will probably be his last, as the satellite is scheduled for launch next April by a Delta II rocket from Vandenberg Air Force Base. His mentor, Steven Frautschi, is professor of theoretical physics, and served as master of student houses from 1997 until July this year.

Jürg Waser
1916 – 2002



Retired Caltech chemistry professor Jürg Waser died of congestive heart failure at his home in La Jolla on August 16. He was 85.

Waser *was* freshman chemistry for a generation of Caltech students. Known for his memorable lecturing style, he filled blackboards with great speed and agility and was infamous for his pop quizzes. Described as a dedicated teacher and supporter of undergraduate research, he was also known for his own work in X-ray crystallography.

Born in 1916 in Zürich, Switzerland, Waser attended the University of Zürich and came to the United States in 1939 intending to spend a year on a graduate student exchange program at Caltech. The outbreak of war kept him in Pasadena, where he completed a PhD in chemistry with Linus Pauling in 1944.

His five-part thesis covered several aspects of electron and X-ray diffraction. He remained at Caltech as a mathematics instructor, research fellow, senior research fellow, and Noyes Fellow until 1948, when he accepted an appointment at the University of Zürich and, later, at the Rice Institute (now Rice University) in Houston, Texas.

Waser returned to Caltech in 1958 as professor of chemistry, and for the next 12 years he taught Chem 1, the general chemistry course for freshmen. Before his retirement in 1975, he taught the basic course in physical chemistry as well as oral presentation, by then the only required course in the chemistry curriculum.

At one time, Waser was president of the American Crystallographic Association, was active in other professional societies, and wrote numerous technical and educational articles.

Upon his retirement from Caltech, he concentrated on writing texts on general and physical chemistry and continued to do research, including work in chemical thermodynamics. He also collaborated with colleague Hans Kuhn in developing a chemical scenario for the origin of life. He was a supporter of the Summer Undergraduate Research Fellowship program at Caltech and felt that it was very important for students to have an opportunity to do research even at the freshman level. He was a member of the Caltech Associates and traveled on Alumni Association excursions.

He loved logic and mathematics, music (ranging from jazz to classical), and the outdoors, especially the landscapes of the American southwest. For most of his life he jumped at an opportunity to camp in the desert, preferably with a railroad in view.

He is survived by his wife Irma; three children, Peter, Nickolas, and Katherine; a grandson, Andrew Waser; and a stepson, Ray Weiss (BS '64). □ — *JP*

David W. Morrisroe
1932 – 2002

Former Caltech vice president David Morrisroe, of Montecito, California, died Wednesday, September 4. He was 70.

A native of New York City, Morrisroe earned his BA from Manhattan College in 1954, his MA from Columbia in 1956, and his MBA from Harvard in 1964. He also served in the U.S. Army as a lieutenant. Before coming to Caltech, Morrisroe held positions at the Rand Corporation and General Electric. From 1967 to 1969 he was in Israel, Spain, and England as a consultant on general management problems.

He came to Caltech in 1969 as director of financial services, and was promoted to vice president for financial affairs and treasurer in 1974. He was appointed vice president for business and finance and treasurer in 1978, and in 1995 became vice president and treasurer. He stepped down in 1995.

The Morrisroe Astroscience Laboratory and the Morrisroe Professorship of Physics, held by Ed Stone, were named in his honor.

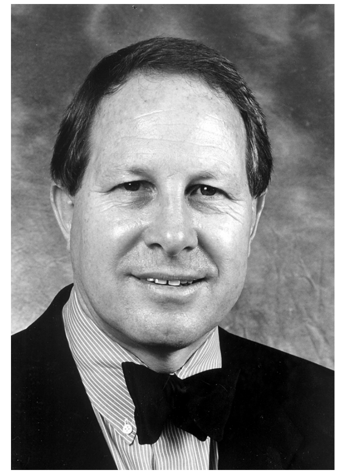
Morrisroe was a popular speaker on such topics as managing not-for-profit corporations, administrative data processing, financial management of educational institutions, and planning. Beginning in 1971, he taught a business economics course, and also founded the Caltech

Student Investment Club.

He was a director of the Harvard Business School Association of Southern California and the Financial Executives Institute of Los Angeles and was a former trustee of the University of San Diego. He was a member of the Academy of Management and the National Association of College and University Business Officers.

He is survived by his wife, Marie. □—*JP*

Hoffmann New Dean of Grad Studies



Michael Hoffmann, the Irvine Professor of Environmental Science at the California Institute of Technology, has been appointed dean of graduate studies. Hoffmann replaces D. Roderick Kiewiet, who returned to full-time professorial duties earlier this year.

Hoffmann has been on the Caltech faculty since 1980. An expert in environmental chemistry, he is a member of the editorial boards of the American Chemical Society's scientific journals *Environmental Science and Technology* and the *Journal of Physical Chemistry*. He is also on the Scientific Advisory Board of the Max Planck Institute for Chemistry in Mainz, Germany.

Hoffmann was awarded the von Humboldt Prize in 1991 for his research and teaching in environmental chemistry. In 2001, Hoffmann was presented with the American Chemical Society Award for Creative Advances in Environmental Science and Technology for "his fundamental and lasting contributions to the science of aquatic chemistry, to the development of aquatic remediation processes, and to understanding heterogeneous and multiphase processes in the atmospheric environment." This year Hoffmann was honored as the Dodge Distinguished Lecturer in Chemical Engineering at Yale.

Before coming to Caltech, he was a member of the civil engineering faculty at the University of Minnesota. He holds a PhD in chemistry from Brown and a BA from Northwestern. He was a research fellow at Caltech from 1973 to 1976. □—*RT*

Honors and Awards

Erik Antonsson, professor of mechanical engineering, has been appointed JPL's chief technologist, where he will be responsible for keeping abreast of cutting-edge technologies and identifying those in which JPL should invest for future missions.

Peter Dervan, the Bren Professor of Chemistry, has been selected by the Technion—Israel Institute of Technology to receive the 2002 Harvey Prize in Science and Technology, for his "pioneering studies" in gene regulation by small molecules and "for combining the art of organic synthesis, physical chemistry, and biology to create novel synthetic molecules." Dervan was also recently elected to the American Philosophical Society.

Wolfgang Knauss (BS '58, MS '59, PhD '63), the von Kármán Professor of Aeronautics and Applied Mechanics, and Anatol Roshko (MS '47, PhD '52), the von Kármán Professor of Aeronautics, Emeritus, were honored in June with special symposia devoted to their work at the 14th U.S. National Congress of Theoretical and Applied Mechanics.

Matthew Porteus, a postdoc in President David Baltimore's lab, has received a five-year, $500,000 Career Award in the Biomedical Sciences from the Burroughs Wellcome Fund. Porteus studies gene targeting, in which a gene is introduced into a cell to replace a damaged copy—a promising approach to curing diseases that are caused by mutations of single genes.

Alexander Varshavsky, the Smits Professor of Cell Biology, will share (with Avram Hershko of the Technion—Israel Institute of Technology) the E. B. Wilson Medal, the highest award of the American Society for Cell Biology. The award recognizes "significant and far-reaching contributions to cell biology over the course of a career," in this case work on the ubiquitin system of regulated protein degradation.

Simon Wilkie, assistant professor of economics, has been named chief economist for the Federal Communications Commission, where, on sabbatical leave from Caltech, he will provide independent, nonpartisan advice on interstate and international communications issues. □

Caltech Names Two New Vice Presidents

Margo Marshak

Caltech has named Margo Marshak the new vice president for student affairs. She is Caltech's first female vice president, and the first full-time vice president for student affairs—all previous vice presidents for student affairs were also Caltech faculty members.

Marshak, who will take her new post October 21, is currently the vice president and dean of students at the University of Chicago. She is also an attorney, and brings extensive experience in student affairs to the position.

Marshak served as vice president for student affairs for 10 years at New York University before moving to the University of Chicago. She developed and implemented the large-scale renovation and construction of residence halls at NYU, and set new directions for student affairs at the University of Chicago.

A graduate of the University of Rochester, she holds an MA from the University of Michigan and a law degree from the California Western School of Law. Prior to her appointments as vice president for student affairs, she held vice and assistant deanships at the University of Pennsylvania Law School and the University of San Diego School of Law.

At Caltech, she will be the senior Institute executive responsible for envisioning, leading, advocating for, and managing student welfare and interests. Among the responsibilities she will assume are leadership of the administration and budgeting for the 16 offices that make up the student affairs organization. This includes oversight of the supporting technological infrastructure, implementation of strategic planning and assessment, and working with undergraduate and graduate students to ensure that they flourish during their educational experience at Caltech.

"I'm obviously thrilled to have the opportunity to come to such a great institution," Marshak said. "I'm enormously impressed with the quality of the students, faculty, and administration. The Caltech students I met during the interview process were extremely bright and interesting, and I look forward to getting to know them and working with them on issues that are of interest to them. I'm grateful to the Caltech family for welcoming my husband and me so warmly." ☐—*JP*

Gary Dicovitsky

Gary Dicovitsky has been named the new vice president for development and alumni relations. Dicovitsky, who is currently the vice president for development and secretary to the board of trustees at Pomona College, will take the position in early October. Since joining Pomona in 1995, his many accomplishments as vice president have included leadership of a highly successful five-year comprehensive capital campaign that exceeded its aggressive goal by 37 percent.

Dicovitsky served as director of planned giving at Princeton University for four years before joining Pomona. He also held senior positions at the University of Virginia and Dartmouth College. In addition, he also served as associate athletic director and head coach of the men's varsity basketball team at Loyola College in Baltimore.

A native of Elizabeth, New Jersey, Dicovitsky holds a bachelor's degree in economic geography, with a minor in urban studies, from Dartmouth College, and a master of education degree from Loyola College. He was formerly a certified financial planner. Active in the alumni volunteer leadership at Dartmouth, he has served as president of the Alumni Council and of the class of 1972, as well as a member of the Alumni Council's nominating and alumni trustee search committee and the ad hoc committee to study the Dartmouth College Alumni Council's structure and operation. Other volunteer work has included serving on the boards of directors of the International Foundation and the Princeton Area Planned Giving Council, as well as volunteering his services to the Claremont-area youth basketball program. He is a member of the National Committee on Planned Giving and the Council for the Advancement and Support of Education.

Dicovitsky will be the senior Institute executive responsible for providing leadership for fund-raising and alumni activities. "With an ambitious campaign coming up, we are delighted that we have been able to find someone with Gary's qualifications, extensive experience, and history of accomplishment," said President David Baltimore. ☐—*JP*

Norman Horowitz and Marge Fling in Horowitz's lab in the 1950s.

Biology Is Beneficiary

In 1946, the year that George Beadle succeeded Thomas Hunt Morgan as chairman of the Division of Biology, Marguerite (Marge) Fling arrived in California with a new PhD degree in biochemistry from Iowa State College. Beadle hired her as a research fellow, and she went to work in the lab of Norman Horowitz (PhD '39), now professor of biology, emeritus, who had come with Beadle from Stanford. Marge worked primarily on the biochemical genetics of the bread mold *Neurospora* (the organism that gave Beadle the insights into fundamental genetics that won him the Nobel Prize in 1958), and she published a number of papers with Horowitz.

Beadle soon discovered that running the disorganized biology division was too much to do and decided he needed an administrator. He found one in Gerald (Jerry) Fling, Marge's husband, whom he had hired as a stockroom manager but who turned out to have lots of other abilities, particularly in management. As administrative assistant in the chairman's office from 1948, Jerry took over responsibility for the annual report, grants, personnel, student affairs, and all the division's countless administrative tasks. The Division of Biology became a very tightly efficient organization, and Jerry Fling became the model for the position of "division administrator," which was eventually wisely adopted by all the divisions. When Ray Owen, now professor of biology, emeritus, succeeded Beadle as chairman in 1961, he also inherited Fling. "It was just wonderful for me," says Owen. "Jerry did so much to make the operations of the biology division pleasant, efficient, and effective."

The Flings left Caltech in 1968, after Jerry's heart attack required a less stressful occupation, and bought 15 acres of orchard near Santa Cruz. The fruit trees proved better for his health than division details, and Jerry lived until 1990; Marge died in 1993. But they remembered Caltech in their estate plans and made the Institute the remainder beneficiary of all their charitable trusts. Jerry Fling's trust provided general divisional support for biology, and Marge's is slated to support fellowships for female grad students in biology. □

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