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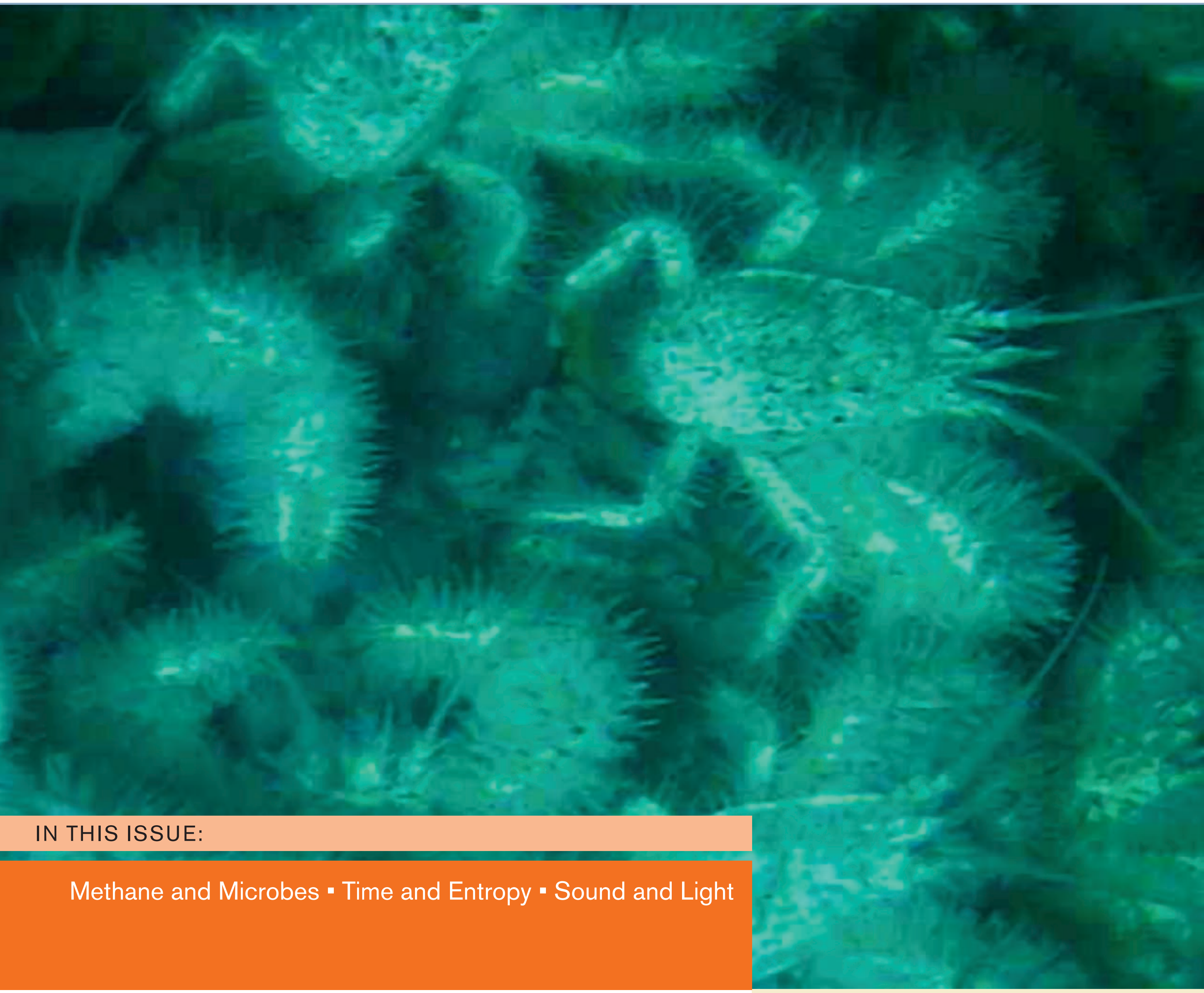

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VOLUME LXXIII, NUMBER 1, WINTER 2010

California Institute of Technology

**ON THE COVER**

Hundreds of blind Yeti crabs crawl on top of each other 1,000 meters underwater off the coast of Costa Rica. Scientists aboard the *Alvin* submersible first discovered the species in 2005 near Easter Island. Researchers from Assistant Professor of Geobiology Victoria Orphan's lab took this picture in February 2009, also from aboard *Alvin.* To see what Orphan's lab has been discovering on the seafloor, turn to page 12.

## "PLENTY OF ROOM AT THE BOTTOM" TURNS 50

What is frequently cited as nanotechnology's seminal paper was published in these very pages in the February 1960 issue. The article, subtitled "an invitation to enter a new field of physics," is an adaptation of a talk given by Caltech's Richard P. Feynman, Nobel laureate in physics and freelance visionary. In it, he discussed possible ways to manipulate matter on the atomic and molecular scale, and what the consequences might be for information storage and chemical synthesis, among other applications.

But, like any good prophet, Feynman was too far ahead of his time to be taken seriously. The after-dinner speech, given in the year-end doldrums on December 29, 1959, at a Caltech-hosted meeting of the American Physical Society, was greeted with "amusement. . . . It simply took everybody completely by surprise," audience member Paul Shlichta (PhD '56) said later. (See "Apostolic Succession" by Christopher Toumey, *E&S* 2005, Nos. 1/2.)

And, for the most part, there things stood until the mid-1980s, when technology finally caught up. "Plenty of Room" was slowly rediscovered in the late 1980s and went viral, as it were, in the 1990s, as early explorers of the nanoworld began to realize that Feynman had, once again, been there first. In fact, things have now gotten to such a point that "it is an unwritten rule on *Nature Nanotechnology* that Richard Feynman's famous 1959 lecture 'There's Plenty of Room at the Bottom' should not be referred to at the start of articles unless absolutely necessary," wrote editor in chief Peter Rodgers in the December 2009 issue, which devoted eight pages to commemorating the anniversary. Not that Rodgers has anything against the talk, he went on to say—he'd simply like to see a little variety in his opening lines. (He forbids references to Moore's Law for the same reason.)

Among the slew of observances here and abroad, the Kavli Nanoscience Institute at Caltech will be celebrating "Plenty of Room" and the upcoming 50th anniversary of *The Feynman Lectures on Physics* on December 9 and 10 with a series of public lectures modeled after the TED conferences. Beyond the usual talks, there will be video clips of Feynman himself, as well as "entertainments" reflecting his many other interests. The details are still in flux, but bongo drumming and an appearance by the Tuvan throat singers are pretty much guaranteed. Check http://feynman.caltech.edu for updates.

In the end, the article's best tribute is the article itself. "Re-reading 'Plenty of Room' with its bizarre mix of angstroms and inches, with Feynman's verve and back-of-the-envelope calculations, with its insights and red herrings, with the benefit of hindsight, is always rewarding," Rodgers concludes. "If you have never read it, you really should." *—DS* e&s

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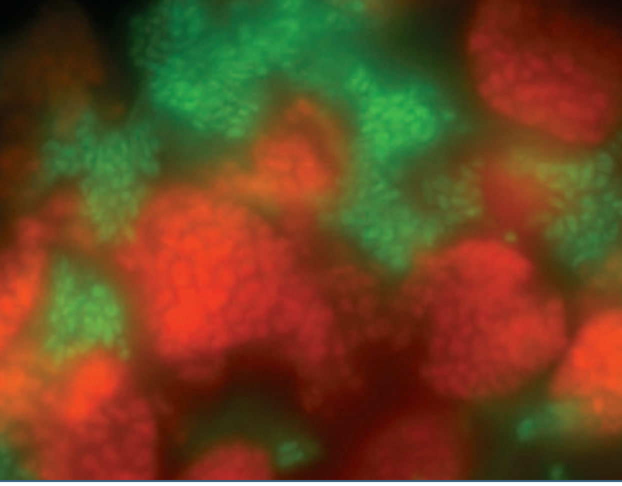

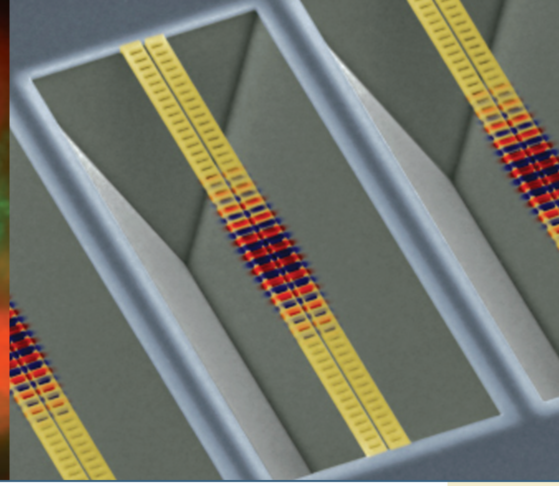

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**Contributing Writers**
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# ANNENBERG CENTER DEDICATED

On October 30, 2009, Caltech's newest building officially opened its doors. The Walter and Leonore Annenberg Center for Information Science and Technology (IST) will house members of the IST initiative, now scattered across campus. As Engineering and Applied Science Division Chair Ares Rosakis remarked at the dedication, "Many universities have created schools of information science. These programs generally focus on hardware and software. IST, in contrast, is based on the concept of information as a unifying principle. We have gathered people from computer science, physics, biology and bioengineering, economics, applied mathematics, computation and neural systems, applied physics, control and dynamical systems, and electrical engineering to think together about the fundamental theoretical underpinnings of information as well as its practical applications, such as computing with DNA, creating tunable biological circuits, understanding complex social systems, and designing a 'smart' electric grid."

"IST is about connecting different areas of scientific and engineering inquiry," says Peter Schröder, professor of computer science and applied and computational mathematics, and chair of the building committee. "We wanted to create a structure where you have a lot of transparency. People see each other; people get inspired by noticing something. You don't want people to just disappear behind closed doors." As a result, windows proliferate inside as well as outside. This ubiquity of glass allows sunlight to shine in from a spacious, two-story central atrium, flooding every office with the light that's often rare in other structures—no grad students toiling in dungeon-like basements here. Fresh air also flows into the building through operable windows in nearly every office.

Natural light and air make Annenberg a comfortable place for contemplation—one of the guiding principles behind the center's architecture, says Schröder. "A building is not going to generate an idea. It's the people in the building that generate the ideas. But if the people are happy and they have pleasant encounters with their fellow occupants, then that's going to support cross-fertilization between disciplines."

Office doors are slightly recessed, leading to jagged hallways that avoid the institutional, sterile feel of

Above left: Windows on three sides let sunlight play over the lounge that projects from the northeast corner of the new Annenberg Center for Information Science and Technology. The indoor picnic table in front of the spiral staircase is a popular lunch spot.
Opposite: The lounge's second floor has a whiteboard within arm's reach of the comfy chairs. There's also a rocking chair to stimulate deep thoughts—or a brain-refreshing doze.

The Annenberg Center fronts on the Moore Walk, opposite Avery House.

seemingly infinite corridors. Along the hallways and in corners, chairs and small tables beside whiteboards stocked with markers encourage impromptu discussions and, one hopes, fresh ideas. "These sorts of things are architectural theory until you see them actually used," Schröder says, but one day he did see some grad students arguing over equations on the board. "That was one of those little moments where I felt pretty good about what we had done, that we had at least accomplished some of these lofty goals." Tables and chairs scattered on the terrace on the north side of the building invite people to sit and linger, and there's even an outdoor blackboard at the building's southwest corner for scientific debates.

Well-designed spaces don't cost much more, Schröder says, and it's worth it to improve the general well-being of the building's inhabitants. For example, the designers chose furniture to be warm and relaxing, which goes a long way toward making people comfortable. Even the wall clocks, with their colors and astral shapes, are from a classic design by George Nelson, a founder of the American Modernism school. And the rich wood paneling found throughout the building is not only pleasing to the eye, but is actually bamboo—a sustainable material.

The building, designed by Frederick Fisher and Partners, is among several Caltech construction projects on track for gold certification under the Leadership in Energy and Environmental Design (LEED) rating system. The center's building materials have at least 20 percent local—minimizing transportation and labor costs—or recycled content. The building also uses 25 percent less energy and 30 percent less water than California state law requires. The designers also minimized the use of harmful chemicals called volatile organic compounds, a feature chiefly noticeable by the lack of those new-paint and new-carpet smells.

Annenberg's operable windows are another design triumph. Central heating and cooling systems don't work well with open windows, but fresh air was seen as so important that independent climate controls were built into each room. This would have been significantly more expensive, were it not for an energy-efficient heating and cooling system that circulates hot and chilled water above the ceiling panels to adjust the temperature. This system is new to Caltech, although common in Europe, Schröder says. And because it doesn't require big aluminum air ducts snaking overhead, the spaces between stories are smaller, which saves even more money—both in construction and operating costs.

Aesthetically, the building echoes the architectural rhythms of the campus, notes Schröder. The outdoor stairways reflect the styles of Spanish architecture (as an added bonus, they save more money by not needing walls and a roof around them), as do the repeating window patterns. The green exterior mimics the hues of olive leaves on the trees that dot the campus.

The center houses 16 research units. There are no wet labs; instead, each unit has a common room called a "studio." But there's a lab full of workstations for undergrads to use on class projects, and a machine room packed with high-powered cluster computers that serve the entire campus.

The building's culture is decidedly egalitarian: all the offices are roughly the same size (although grad students and postdocs still have to share space with each other), and the best areas are shared by all: the northeast lounge, for example, boasts sweeping views of the San Gabriel Mountains. "The idea was that the best, most beautiful piece of real estate should be made public," Schröder says.

Left: Floor-to-ceiling windows opening into the atrium let light into the research groups' studios. The "trellis" of jigsawed bamboo was generated by a random-line algorithm as a representation of a densely connected network. Below: Hidden therein is a Caltech beaver.

Good design is more than just good looks, Schröder argues. It makes a "difference in the quality of our lives, in the mood of our spirits, and in the loftiness of our creative flights." How high these creative flights go remains to be seen. "We'll have to give it a year or two before we can truly evaluate how various things are working out," he says. "But so far, so good."

Built by Hathaway Dinwiddie, the $31 million building was made possible by the Annenberg Foundation and by Stephen Bechtel Jr. The Moore Foundation provided the seed funding for the IST initiative. —*MW* e&s

*The Annenberg Center dedication video is available online, as is an interview with Jehoshua "Shuki" Bruck, founding director of the IST program and the 2008 winner of Caltech's Feynman Prize for Excellence in Teaching. You can also view a slideshow of interior and exterior pictures of the Annenberg Center.*

# UBIQUITIN'S KISS OF DEATH

Ubiquitin is a molecular stoolie, fingering other proteins for destruction by a cell's molecular trigger men. But don't feel bad for the victims—they all need to die. Some are molecules whose job is done, such as messengers whose signal has been sent. Others might be old and falling apart, or perhaps didn't form properly in the first place. Ubiquitin fingers its marks for the whisper chipper by attaching a chain of four or more copies of itself to the soon-to-be-departed, but like any good hit, it all happens so fast that you can't see it coming.

Until now, that is. Nathan Pierce, a grad student in the lab of Raymond Deshaies, a professor of biology at Caltech and a Howard Hughes Medical Institute investigator, has created a sort of biological stop-motion animation based on a piece of apparatus called a quench-flow machine that allows you to stop, or quench, a reaction after a very precise interval of time has elapsed—for these studies, in increments of 10 milliseconds. Previous studies had looked at the reaction on the scale of seconds or minutes, which "did not have sufficient time resolution to see what was going on," says Deshaies. "It's as if you gave an ice-cream cone to a child and took a picture every minute. You would see the ice cream disappear from the first photo to the next, but since the pictures are too far apart in time, you would have no idea whether the kid ate the ice cream one bite at a time, or swallowed the entire scoop in one gulp."

In this case, the question was whether the ubiquitin molecules got added one at a time, or did the entire preassembled chain get added in one go? It was already known that three different enzymes, dubbed E1, E2, and E3, are involved in the process. E1 readies the ubiquitin for transfer, then hands it off to E2. A form of E3 called a RING ligase (RING stands for "really interesting new gene") then binds to the E2 and the target protein simultaneously, causing the E2 to transfer the ubiquitin molecule to the target. "The process is so complicated and so fast," Pierce notes, "that we weren't able to see how the chain is actually built."

It turns out that the ubiquitins are attached one by one, and a paper by Pierce announcing this appeared in the December 3, 2009, issue of *Nature*. In addition to Pierce and Deshaies, the other authors were postdoc Gary Kleiger and Assistant Professor of Chemistry Shu-ou Shan.

The next task was to figure out how the process works so quickly. One answer was provided in a parallel study spearheaded by Kleiger. He showed that E2 and E3 interact with each other at a blistering pace while building the chain—far faster than is commonly seen in protein trysts. As is often the case with humans, opposites attract, and the enzymatic speed dating is enabled by an acidic tail on E2 that nestles into an alkaline canyon on E3. Kleiger's work appeared in the November 25, 2009, issue of *Cell*; the other authors included Caltech postdoc Anjanabha Saha, Steven Lewis and Brian Kuhlman of the

University of North Carolina at Chapel Hill, and Deshaies.

Deshaies now wants to find the reaction sequence's slowest step, the one that sets the speed limit for the entire process. By finding the slowest step and making it slower, he says, the enzymes "may become too slow to get their job done—to build chains—in the time available to them to do so. Being able to develop drugs to block their function would open up a new frontier in medicine."

The work was funded by a Gordon Ross Fellowship, the National Institutes of Health, and the Howard Hughes Medical Institute. *—LO*

## DIM AND DIMMER

Out in the deep, dark reaches of the solar system beyond Neptune's orbit lies the Kuiper Belt, a vast ring of icy bodies big and small—including the Pluto formerly known as planet. Now, a Caltech-based team has used the Hubble Space Telescope to spot the smallest object ever seen out there—a chunk of debris only one kilometer in diameter. Over 1,000 Kuiper Belt objects have been discovered to date, but the next smallest one is roughly 30 kilometers across.

This piece of coal-black rubble from the birth of the solar system is some 6.7 billion kilometers away—half again as distant as Neptune—and 100 times dimmer than anything that the Hubble can see directly. Instead, the team used data from Hubble's fine guidance sensors, which lock onto various guide stars in order to keep the telescope trained on whatever the astronomers happen to be studying. The sensors collect the guide stars' light 40 times per second in order to measure the slightest changes in their positions, enabling the Hubble to stay rock-steady in its gaze.

Grad student Hilke Schlichting (MS '07, PhD '09) sifted through four and a half years of this tracking data, looking for any momentary dimmings of guide stars caused by Kuiper Belt denizens passing between them and us. Specifically, she was searching for a telltale diffraction pattern caused when an interloper intrudes on our line of sight—a new twist on the old high-school optics experiment using a slit and a light bulb, with the Kuiper Belt object acting as the slit.

## NOW YOU SEE WHAT WISE SEES

A star, a star, burning in the night; it's the picture of WISE's first light. It's the picture from WISE's first light.

The Wide-field Infrared Survey Explorer, launched on December 14, 2009, has doffed its lens cap and snapped its first image—of a dim red star called V482 Carina that would be just barely visible to the naked eye. In the background are some 3,000 other stars in a field of view about three times the area of the full moon.

For the next nine months, WISE will be taking a picture once every 11 seconds, mapping the entire infrared sky one and a half times and revealing everything from dark asteroids nearby to dusty galaxies 10 billion light-years away. The science team includes Assistant Professor of Astronomy Andrew Blain, Members of the Professional Staff Roc Cutri, Thomas Jarrett, J. Davy Kirkpatrick, and Deborah Padgett (PhD '92), plus Peter Eisenhardt, T. Nick Gautier, Amy Mainzer (MS '01), and Michael Ressler of JPL. Caltech's Infrared Processing and Analysis Center is compiling the data.

JPL is managing the mission; the spacecraft was built by Ball Aerospace, and the instrument by Utah State University. *—DS*

The data, from 12,000 hours of telescope time, yielded exactly one occultation in the swath of sky extending 20 degrees from the solar system's ecliptic plane, where the Kuiper Belt is expected to be densest. Based on downward extrapolations from the known population, the team had expected to turn up more than 20 bodies in the 300-meter size range. The whopping deficit supports the notion that these comet-sized objects are continuously colliding and grinding one another down, which would mean that the Kuiper Belt's dwellers are evolving—they aren't simply static souvenirs of our solar system's formation, safely stored in the deep freeze.

Furthermore, says the *Nature* paper describing the find, this pulverization process "provides the missing link between large Kuiper Belt objects and dust, producing [the] debris disks [observed] around other stars."

Schlichting's paper was published on December 17, 2009. The other authors are Caltech postdoc Eran Ofek; Mike Wenz of the Goddard Space Flight Center; Associate Professor of Astrophysics and Planetary Science Re'em Sari; Avishay Gal-Yam, a senior scientist at the Weizmann Institute of Science and a visiting associate in astronomy at Caltech; Mario Livio of the Space Telescope Science Institute; Ed Nelan of the Space Telescope Science Institute; and Shay Zucker of Tel Aviv University. —*DS* e&s

# PARALLAX IN MOTION

Four hundred years after Galileo first turned a homemade spyglass to the heavens, the somewhat larger Hale Telescope at Caltech's Palomar Observatory has discovered a new star, Alcor B, in the Big Dipper—using a technique he foresaw. Says team leader Ben Oppenheimer (PhD '99), of the American Museum of Natural History in Manhattan, "Galileo realized that if Copernicus was right—if the earth orbits the sun—he could show it by observing the parallactic motion of the nearest stars. He tried to use Alcor to see this, but didn't have the necessary precision." Parallactic motion is the way that nearby stars appear to move slightly, relative to the firmament, over the course of a year as we see them from different points in Earth's orbit.

Alcor B is a red dwarf about 250 times the mass of Jupiter, or one-quarter that of our sun. The star around which it orbits, Alcor A, is a relatively young star twice the mass of the sun. The Alcors share their position—second star from the end in the Dipper's handle—with another star, Mizar. (In fact, the ability to see both stars—being able to distinguish "the rider from the horse"—was a common test of eyesight among ancient peoples.) One of Galileo's colleagues observed that Mizar itself is actually a double, making it the first binary star system resolved by a telescope. Many years later, Mizar A and B were each found to be tightly orbiting binaries, altogether forming a quadruple system.

Last March, members of Project 1640, a collaborative hunt for planets orbiting other stars, attached their coronagraph—a device for blocking out a star's light, allowing faint objects nearby to be seen—to the Hale and aimed it at Alcor. "Right away I spotted a faint point of light next to the star," says Neil Zimmerman, a grad student at Columbia who is doing his dissertation at the museum.

The team returned 103 days later, hoping to find that the two stars had moved as one. If the proposed companion was just a background star, it wouldn't necessarily be keeping Alcor company any more. But the two had, indeed, moved in tandem, says Oppenheimer. "Our technique is much faster than the usual way of confirming that objects in the sky are physically related." If the putative pair is too far away for parallax, you may have to watch them for years in order to measure any motion.

The Alcors are about 80 light-years away, and over one year they appear to move in an ellipse about 0.08 arc seconds long. This is about 1,000 times smaller than the eye can discern—but easily detectable with the coronagraph's adaptive optics, which remove the distorting effects of atmospheric turbulence and thus allow very fine position measurements to be made.

"We hope to use this technique to check that any potential exoplanets we find are truly bound to their host stars," says Zimmerman.

"Red dwarfs are not commonly reported around the brighter, higher-mass type of star that Alcor is, but we have a hunch that they are actually fairly common," says Oppenheimer. "This discovery shows that even the brightest and most familiar stars hold secrets we have yet to reveal."

The Project 1640 collaboration includes researchers from the American Museum of Natural History, the University of Cambridge, and the Space Telescope Science Institute, as well as Associate Professor of Astronomy Lynne Hillenbrand, Senior Faculty Associate in Astronomy Charles Beichman, postdocs Sasha Hinkley and Justin Crepp, adaptive optics engineer Antonin Bouchez (PhD '04), and Member of the Professional Staff Richard Dekany (BS '89) from Caltech, and Gautam Vasisht (PhD '96), Rick Burruss, Michael Shao, Lewis Roberts, and Jennifer Roberts of JPL. Project 1640 is funded by the National Science Foundation.
—*SK* E&S

Gregory Chamitoff (MS '85) ponders his next move in the galaxy's first "Earth vs. Space" chess match while aboard the International Space Station. (Earth won.) Chamitoff, who spent 183 days on the station in 2008, also took time out while in orbit to participate, via video downlink, in the 80th-anniversary celebration of the Graduate Aerospace Laboratories at Caltech (GALCIT). Chamitoff returned to campus on October 26, 2009, to give the annual Klein Lecture in Aerospace Engineering. Afterward, he presented GALCIT with a banner emblazoned with a caricature of GALCIT founding director Theodore von Kármán that Chamitoff had taken with him to the space station.

## THE SOLAR ARMY IS RECRUITING

In the battle to save the world from global warming, the newest weapons are LEGO Mindstorms robotics kits, inexpensive lasers, and ink-jet printers that spit out metal salts instead of ink. The newest recruits are high school students, guided by generals from Caltech's chemistry department. The objective is to locate a metal oxide that can use sunlight to split water into hydrogen, a storable fuel, and thus wean us from fossil fuels.

The project is the brainchild of Bruce Parkinson (PhD '78), now a chemistry professor at the University of Wyoming, who got the idea while watching his own high-school-age children playing with LEGOs. Parkinson combined LEGOs with a laser pointer and other cheap, readily available components to create a $600 computer-controlled, gear-driven testing device that very precisely scans a laser beam across three-millimeter-diameter metal-oxide samples printed on CD-sized glass slides. As

From left: Postdoc Bryce Sadtler, grad student James McKone, and grad student Jillian Dempsey give a lunchtime presentation at John Muir High School in Pasadena.

Carolyn Valdez (right) explains the setup to Chelsea Newbold (left), an 11th-grader at Blair High School. The slide to be scanned goes in the frosted-glass tank at the right. The laser beam is marched across the slide by a pair of angled mirrors (follow Carolyn's fingers) facing each other and mounted on two perpendicular assemblies of gears and connecting rods driven by the Mindstorm motor units (the gray cylinders, one of which is obscured in this view); the laser pointer itself rests behind the one red LEGO brick in the cradle at the left of the apparatus.

the metal oxide pixels get illuminated one by one, the electrical current generated by this artificial sunlight is measured for each one.

Parkinson and Caltech's Powering the Planet Center for Chemical Innovation have parlayed this gizmo into a project called SHArK, for Solar Hydrogen Activity Research Kit. (The small "r" allows the acronym to be written as a sequence of chemical elements.) Initially funded with seed money from the Dreyfus Foundation and now supported by the National Science Foundation, SHArK has the potential to rally young people around the globe to collaborate on solving a real-life problem.

"We've been flooded with requests from students and parents who want to join the Solar Army," says Harry Gray, the Beckman Professor of Chemistry and a member of the center. "There are millions of possible metal oxide combinations that might work. We need thousands of students to check them out. We don't have a really good idea which combinations will be the winners."

The winners will be dirt-cheap, nontoxic, readily available compounds that can mimic photosynthesis and split water into hydrogen (to run a fuel cell to produce electricity; unlike sunlight, hydrogen can be stored for use at night) and oxygen. Plants photosynthesize with organic molecules that they replace every 30 minutes or so because oxidation is a brutal process that degrades living tissue. But an inorganic, metal-oxide catalyst would be able to withstand oxidation, because it's already oxidized.

Finding that catalyst is a little like locating a rusty needle in the periodic haystack of elements. The best candidate will probably consist of an oxide containing three or four metals working together in order to absorb as broad a spectrum of sunlight as possible. That's the easy part. The hard part is that the metal-oxide combo must then spit out electrons that are energetic enough to split water.

Grad students Jillian Dempsey, Suzanne Golisz, James McKone, and Leslie O'Leary, undergrad Carolyn Valdez (BS '10), and postdoc Bryce Sadtler are mentoring student volunteers at three local high schools—Blair High School, John Muir High School, and Polytechnic School. Each student group is given their own kit to assemble, and is shown how to print their own slides and how to use the scanner.

The project was born in 2004 when Parkinson, then at Colorado State, started work on a method to retrofit ink-jet printers to handle metal nitrate salt solutions rather than ink. Heating the slides to 500°C then transforms the salts into metal oxides. Nate Lewis (BS '77, MS '77), Caltech's Argyros Professor and professor of chemistry, who had overlapped with Parkinson at Caltech while a student, heard about the work at a meeting and dispatched grad student Jordan Katz (PhD '08) and undergrad Todd Gingrich (BS '08) to visit Parkinson's lab. The Lewis lab then adapted the idea, improving the design so that it yielded more data per sample.

Each slide contains 16,200 unique metal oxide samples grouped in four adjoining triangles. Each triangle contains oxides of three different metals in a gradual continuum of concentrations, ranging from equal amounts of all three metals at the triangle's center

"There are millions of possible metal oxide combinations that might work. We need thousands of students to check them out."

point to 100 percent of one metal at each tip of the triangle. Each slide also has two smaller triangular arrays of metal oxides with known photoelectric behavior, used for calibrating the measurements.

In a process that takes some six to eight hours per slide, a pulsed green laser slowly scans each pixel while the slide is suspended in an electrically conductive solution of sodium hydroxide. If a metal oxide splits water, current will flow through the solution to an electrode, registering a "hit." Teams share their information on the infobahn, and if the hit is validated by another high school or college, the formulation will be further tested at Wyoming or Caltech. Eventually, of course, we'll have to figure out how to produce enough of the winning stuff to support the power grid.

The project continues to expand, and Parkinson and Gray plan to extend their recruiting activities to more colleges and high schools. (See www.thesharkproject.org for more information.) "These are the kids who are going to make the difference as to whether we're going to have solar energy," says Gray. "This is the future of the planet. And, by the way, it's your future." *—LD* E&S

# INTRABODIES R US

About 30,000 Americans suffer from Huntington's disease, a gradual loss of brain cells that affects the ability to speak, move, and even think. There is no cure as yet, but now a way to slow the disease's progress may have been found by Caltech scientists.

Huntington's has its roots in a mutation in the gene for a protein called huntingtin. Huntingtin is essential for normal brain development, although its exact function is unclear. The mutation creates an abnormally long version of the protein, which normally contains a string of 10 to 35 copies of an amino acid called glutamine. The mutation has a genetic stutter, causing this string to lengthen to as many as 120 glutamines. The abnormally long protein gets chopped up into smaller pieces that accumulate in a part of the brain called the basal ganglia, eventually killing the cells. As the cells die, decision-making skills and memories fade, coordination decreases, and twitches set in in the fingers, feet, and face.

Back in 2002, Senior Research Fellow in Biology Ali Khoshnan, biology staff member Jan Ko, and Paul Patterson, the Biaggini Professor of Biological Sciences, discovered that certain molecules could bind to the mutant protein and either block or exacerbate the mutant's toxicity. These molecules belong to a class of molecules now known as "intrabodies," or intracellular antibodies, because they work like antibodies but operate inside a cell rather than binding to a target protein on the cell surface. The intrabody gets into the cell by hitching a ride on a tame virus, which then hijacks the cell's machinery to flood the cell with it.

Now, grad student Amber Southwell (PhD '09), Ko, and Patterson have shown that an intrabody called Happ1 can reverse much of the loss of coordination and cognition in five different strains of mice bred to mimic various aspects of Huntington's disease—the first time this has been demonstrated so effectively in mammals. (Previous studies had used cell cultures or fruit flies.) In one strain, Happ1 actually increased the mouse's body weight and life span.

Happ1 binds to an amino-acid sequence unique to the huntingtin protein that is rich in the amino acid proline, and this sequence is expected to be extremely specific. "Our studies show that the use of intrabodies can block the parts of mutant huntingtin that cause its toxicity without affecting

**PICTURE CREDITS**
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The “SOLD” banner comes down from the facade of MIT’s Building 10. Had things gone according to plan, the banner would have been visible from the Charles River.

the wild type, or normal, huntingtin—or any other proteins,” says Patterson.

In other words, he says, this has the potential to be the kind of “silver-bullet therapy” that many medical researchers look for. Current treatments tend to address the disease’s symptoms, not its cause, but this approach might prevent it from doing significant damage in the first place.

The next step, says Patterson, is to improve the intrabody’s effectiveness and to “build a viral vector that can be controlled—induced and turned off—in case of unexpected side effects. This is a general goal shared by all types of experimental gene therapies.”

A paper describing the work, with Southwell as the lead author, was published in the October 28 issue of the *Journal of Neuroscience*. The research was funded by the Hereditary Disease Foundation, the CHDI Foundation, and the National Institute of Neurological Disorders and Stroke. —*LO* e&s

## SO CAL’S SEISMO STIMULUS

A major upgrade is under way at the Southern California Seismic Network, jointly operated by Caltech and the U.S. Geological Survey. The $3.2 million project is part of an overhaul of all of the USGS’s networks that is being funded by federal stimulus money for infrastructure improvements.

Locally, this means new equipment at 138 out of some 300 monitoring stations, and minor upgrades at 40. The original units were deployed in the 1990s as part of the TERRAscope and TriNet projects. The off-the-shelf digitizers available nowadays are much more compact and draw less than a watt of power, says David Johnson, Caltech’s lead field installer, “which is really significant when we go solar at our sites.”

Besides making fundamental improvements to the network’s data quality and reliability, “the new equipment will log data fast enough to allow us to develop algorithms for an early warning system,” says Senior Research Associate in Geophysics Egill Hauksson, who is in charge of Caltech’s end of the project. However, he notes, an actual warning system would require many additional stations and remains years away.

The current project, which started last October, will be finished in September 2011. —*DS* e&s

## SOLD!

“Bowing to extreme financial pressures, MIT administration today made official the sale of the Institute to Caltech. The campus is to be repurposed as Caltech East, a new School of the Humanities, serving as a complementary counterpart to Caltech’s scientific excellence,” read the top story of the Monday, November 30, 2009, issue of *The Tech*, the MIT student newspaper. The changeover would include reassigning all MIT undergrads to new majors in the new school, the paper went on to say. “While East Campus students will still be held to the same high academic standards to which they are accustomed, they will be relieved of the responsibility of advancing human knowledge through scientific research.” As part of the formalities, a giant SOLD banner would be hung in Killian Court to greet students returning from their Thanksgiving break.

Ah, but it was just a Caltech prank.


Following six months of intense planning and reconnaissance, zero hour was 0330 on the 30th. ASCIT president Anthony Chong, a senior, led the operation, ably supported by 18 undergrads and 25 or so alumni who hosted students and picked up and delivered the banners, fliers, T-shirts, and fake newspapers. "Michael Betancourt (BS '06), Kasia Gora (BS '06), and Russell McClellan (BS '09) really stepped up," Chong says. The strike team was divided into three groups.

The roof team unfurled the banners. Besides the SOLD sign, other banners were to be hung along Massachusetts Avenue, MIT's main drag, proclaiming, "Welcome to Caltech East, School of the Humanities."

The corridor team deployed new floor mats featuring the Caltech East seal, an amalgam of the Caltech and MIT logos, and changed the administrators' office-door nameplates. Fliers to be distributed along the way teased readers with announcements of tutorials on such topics as "How to sustain yourself as a freelance writer," and an invitation to join the new Caltech East Surf Club.

Meanwhile, the tech team finished up the Caltech East website, http://east.caltech.edu, which included a pdf of the eight-page bogus *Tech*. (Visit http://east.caltech.edu/tech.pdf to read it.) The lead story's companion photo showed Caltech president Jean-Lou Chameau shaking hands with MIT's Susan Hockfield, "sealing the deal." Other articles included the announcement of a new Caltech East mascot (another beaver) and various orientation materials, including a Caltech glossary and the following handy conversion chart to help befuddled East Techers find their new majors:

- BIOLOGY: Biology
(Keep it. This science is so soft it might as well be a humanities option.)
- CHEMISTRY: Foreign Language
(Considering IUPAC nomenclature, I'd say you're already halfway there.)
- ENGINEERING: Economics
(Hey, they both start with "E" and you still get to do useful math.)
- MATHEMATICS: Philosophy
(At least you're still in a field not applicable to the real world.)
- PHYSICS: Women's Studies
(It's time you guys learned some manners. And how to bathe.)

Alas, despite much practice on Caltech buildings, the SOLD banner did not drop as quickly as anticipated. Other team members were recruited to help, which slowed down the entire enterprise. But ultimately, it was an MIT janitor who doomed the deed. After spotting the new floor mats, and over Chong's protests, the janitor called the MIT police, who have no sense of humor. The pranksters were stopped dead in their tracks and forced to take down all their work. Some of the faux *Tech*s were distributed anyway by alumni unaware that the plot had been foiled, causing—one hopes!—a few confused MIT students.

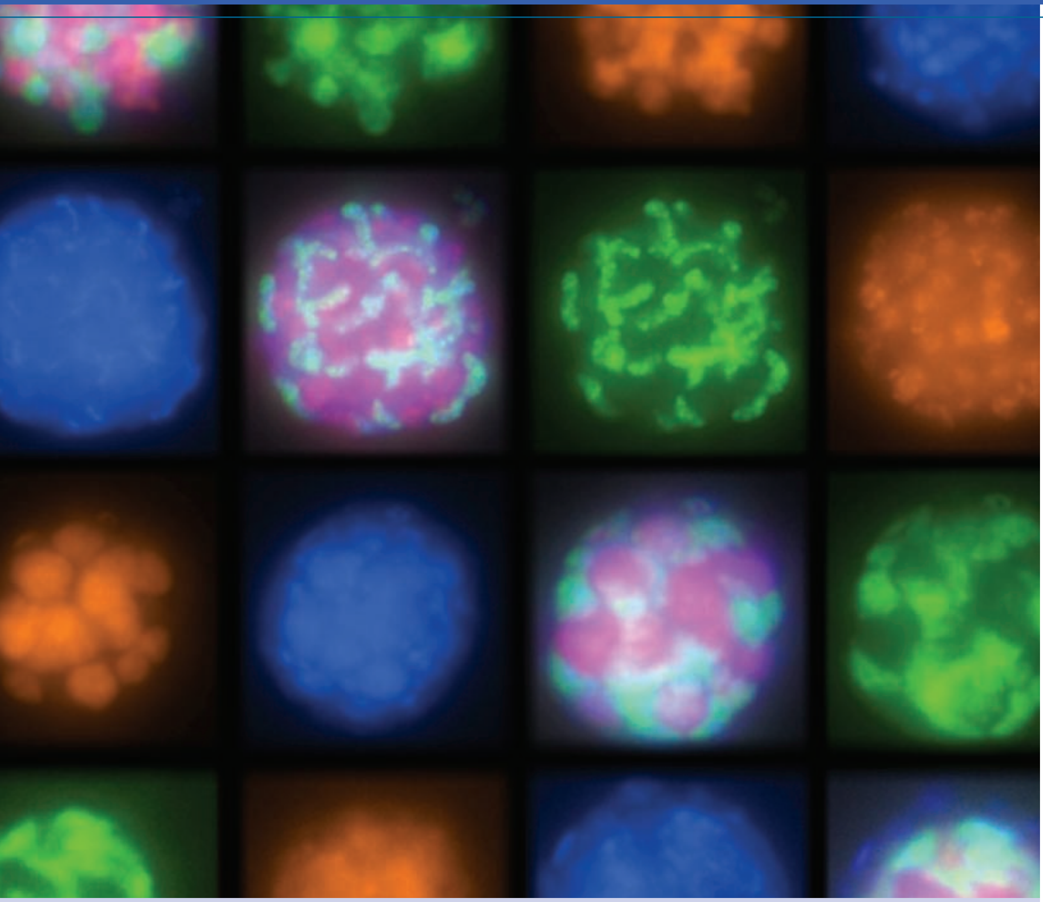
Despite being busted in flagrante, "All in all, I'm pretty happy," Chong says. "We were sooooooo close. Another 10 minutes and everything would have been done."

Oh, well—better luck next time. Thanks to Assistant Vice President for Student Affairs and Campus Life Tom Mannion and some generous alumni, there's now a prank club and some non-Institute funding for future adventures. *—DP* e&s


Left: The prank team. Top row, left to right: Anthony Chong ('10), Sebastian Rojas Mata ('13), Isaac Sheff ('12), John Forbes ('10), Heather Widgren ('10), Raymond Jimenez ('13), Alex Rasmussen ('12). Bottom row: Jordan Theriot ('12), Eugeniu Plamadeala ('10), Ryan Thorngren ('13). Missing: Peggy Allen ('11), Perrin Considine ('12), Megan Larisch ('12), Rebecca Lawler ('13), Julian Panetta ('10), Nicholas Rosa ('10), Stefan Skoog, Will Steinhardt ('11). Right: The new Caltech East seal.

Sixteen panels of four different clumps of marine microorganisms collected from a methane seep off the coast of northern California. Each clump, called an aggregate, is about 10 microns (millionths of a meter) across. The microbes have been tagged with fluorescent markers. DNA glows blue.

# Diving for Microbes

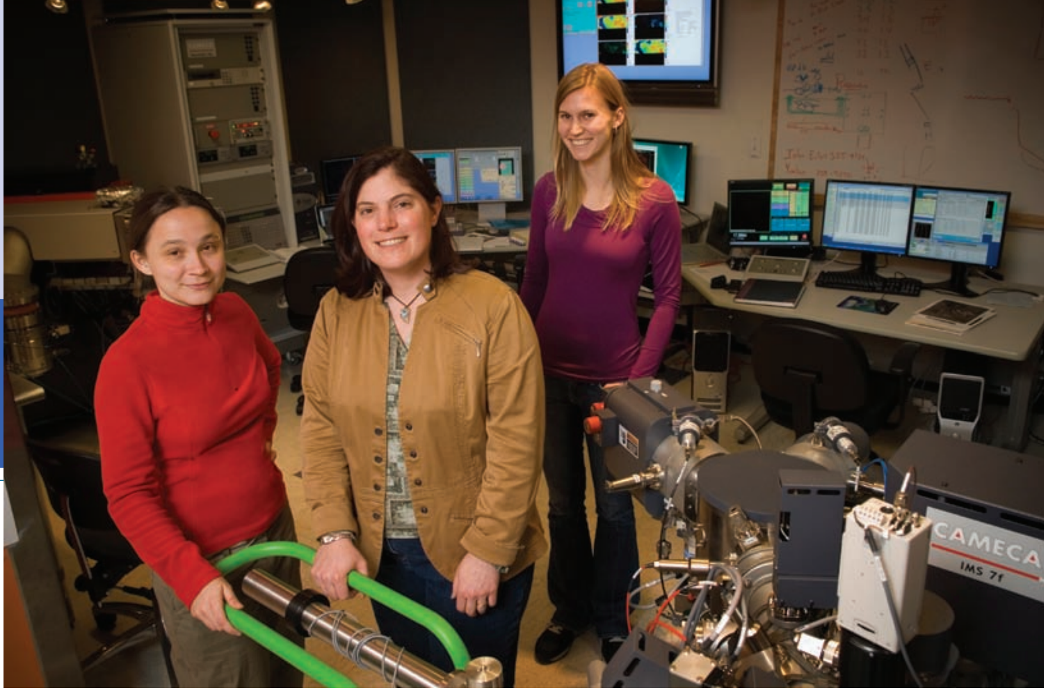


In the harsh conditions of the ocean floor, a mysterious medley of microbes survives by eating methane. By consuming this greenhouse gas, they prevent further warming of the planet. But little is known about these microbes, whose existence is indirectly essential to the rest of life on Earth, so researchers are diving into the sea to find out what secrets they may hold.

Off the western coast of Costa Rica, where the crust of the North American continent ends, the underwater terrain is smooth and barren. A thousand meters deep, the seafloor is beyond the reach of the sun and low in oxygen. "It's just amazing—the bottom of the deep ocean at that site is surprisingly desolate," says Anne Dekas, a graduate student in Assistant Professor of Geobiology Victoria Orphan's lab. "It's just flat and gray sediment for as long as you can see." Breaking the monotony are occasional methane seeps—places where methane trapped in ice (see box) is released and bubbles out through cracks in the seabed—and at these seeps, Dekas says, "it's completely different. It's an oasis of life." Boasting clams, crabs, tube worms, shrimp, and microbial mats, these dark, deep-sea oases are made possible by microorganisms that eat the bountiful methane, producing nutrients and sources of energy for the rest of the food chain.

But these microorganisms do more than just form the foundation of exotic ecosystems—they're crucial for the entire planet. Methane is a powerful greenhouse gas, about 20 times more adept at trapping heat than carbon dioxide. The oceans are estimated to produce anywhere from 5 to 50 million metric tons of methane per year, a significant fraction of the 535 million or so metric tons of total methane annually released into the atmosphere via natural and human sources. Scientists say these deep-dwelling bugs consume about 80 percent of the methane that otherwise would have

Graduate student Abigail Green (left), Orphan (middle), and Dekas, at the Caltech Center for Microanalysis.




By Marcus Y. Woo

been released into the atmosphere from the oceans, so without these tiny critters, the accumulation of extra methane would heat the globe even more, accelerating the climate change that's threatening life on the planet.

These organisms are found wherever there are methane seeps, and despite how important they are, we know very little about them. Only in the last decade have researchers such as Orphan and those in her lab begun to figure out how these creatures live. It turns out that the bacteria form a symbiotic relationship with archaea—another form of microscopic life—to consume methane in oxygenless environments. "From an ecological and evolutionary standpoint, it's a fascinating system, because you have these two very different life forms that have been living together and coevolving together for many millions of years—and maybe many billions of years," Orphan says. Without sunlight or oxygen, these organisms can't produce energy like most of the life we're used to. They must resort to more creative ways, processes that may be similar to those used by the very first life on Earth nearly four billion years ago. As living fossils, they have something to say about the history of our planet.

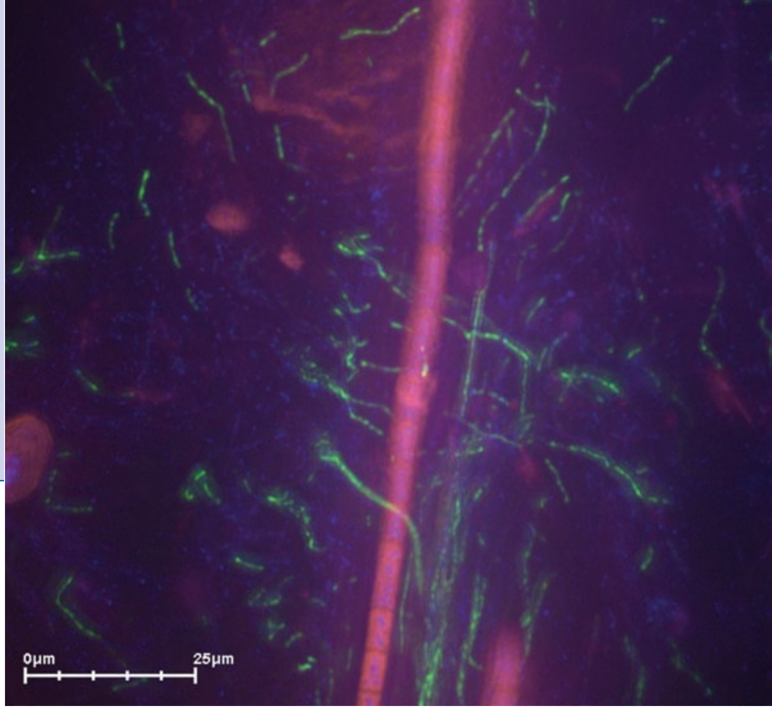
Even though bacteria and archaea—which are as biochemically different from each other as bacteria are from humans—are so small we may forget about them, they far outnumber all other living things on Earth. In your body alone, there are 10 times more bacterial cells than human ones. Scientists estimate that the planet has $5 \times 10^{30}$ microorganisms—that's more than a hundred million times the number of stars in the observable universe. Scoop up all these little critters together, and they'll weigh several hundred billion metric tons, a mass about a thousand times greater than that of all the people on Earth. The majority of the planet's microbes are believed to live inside Earth's crust or just below the seafloor, regions that are scarcely understood and explored, so many more bug-based ecosystems are likely still undiscovered.

Often unjustly maligned, microbes are essential for life. "They are an integral part of almost every facet of our planet," Orphan says. No species of archaea are known to cause diseases, and only a small fraction of bacteria do; most are harmless or even helpful. Bacteria help digestion, and, as biologists are finding, they play essential roles in our immune systems and overall health (see *E&S* 2009, No. 1).

For the rest of the world, microorganisms ensure that carbon, oxygen, sulfur, and other elements critical for life flow through the global ecosystem, providing the nutrients by which every plant and animal exists. "Bacteria and archaea run the planet—chemically speaking—and they have for billions of years," Dekas says. "For instance, the evolution of oxygenic photosynthesis in bacteria is

**FIRE ON ICE**

**Given the right combination of temperature and pressure, methane molecules can get trapped in the crystal structure of water ice to form a so-called methane clathrate (inset), also known as a methane hydrate or simply methane ice. The result is a chunk of normal-looking ice but for one exception: it burns. This cold combustible forms in deep-ocean sediments, but also underneath the permafrost in the Arctic regions. The U.S. Geological Survey estimates that deposits in Alaska contain 2.4 trillion cubic meters of the frigid flammables, prompting some to consider it as a potential fuel source. But even if we never harvest it and burn it, it's still likely to contribute to climate change: as the planet warms, melting permafrost will expose the hydrates, which will in turn melt and release the methane, triggering more warming.** e&s




Using a technique called fluorescence *in situ* hybridization (FISH), the researchers took this image of sulfate-reducing bacteria (green) and cyanobacteria (red) from a bacterial mat. The scale bar is in microns.

the reason there's oxygen in the air." Orphan adds, "As some of my colleagues say, every fifth breath you take, thank a microbe." And in the last year, Orphan's lab discovered that the methane-consuming microorganisms play a surprising role in the global nitrogen cycle. They are among a whole group of bugs that help convert gaseous nitrogen into forms usable by other creatures. Without these microbes, the planet would run out of biologically available nitrogen in less than a month.

**METHANE MUNCHERS**

Most of the life we're accustomed to—be it bird, fish, or human—needs oxygen to harness the energy locked in the chemical bonds of sugars. But instead of glucose, the bacteria and archaea at the seeps take in methane as their food—and they do it anaerobically, that is, without oxygen. Methane, of course, is the main ingredient of natural gas, the fuel that you might use to boil your spaghetti. Clearly, it's easy to extract energy from methane: just add oxygen and a little spark, and you ignite a fiery reaction, in which electrons are transferred from methane to oxygen, producing carbon dioxide, water, and lots of energy. In chemical parlance, the methane is "oxidized" and the oxygen is "reduced."

Without oxygen in the seafloor mud, these microorganisms have to oxidize methane with some other agent. One popular compound is sulfate, a salt abundant in seawater. Geochemists first proposed this process in 1976, when they looked at how the chemistry of the sediment changed with depth and discovered that methane consumption coincided with a decrease in sulfate. Because they knew of no physical process that could cause this curious correlation, they concluded that the origin must be biological—some organism was oxidizing methane and reducing sulfate.

The problem, though, was that combining methane and sulfate produces so little energy that nobody thought it could support any sort of life. Some microbiologists tried to grow a sulfate-reducing organism with methane as its sole carbon and energy source in the lab, Orphan says, but they were unsuccessful. Now, researchers know that the conditions at methane seeps (and many other natural environments) are too complex to be easily reproduced in a petri dish—in fact, scientists still haven't been able to grow pure cultures of 99 percent of all known microorganisms. Over the years, follow-up studies about whether anaerobic methane-eaters really did exist would occasionally appear in the literature, but nobody took them that seriously, according to Orphan. "The field remained dormant for several years," she says.

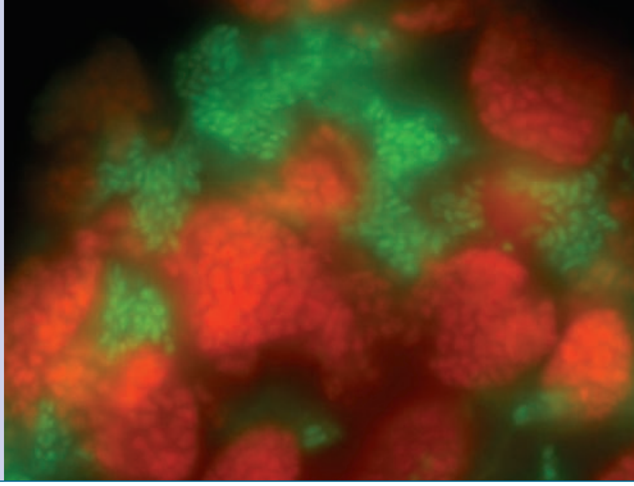
"Several years" ended up becoming two decades before advances in molecular biology provided the tools needed to revisit the mystery of the methane seeps. In 1999, Orphan started working on this problem as a graduate student with Ed DeLong at the Monterey Bay Aquarium Research Institute. There, a collaboration with Kai-Uwe Hinrichs, who at the time was a postdoc at the Woods Hole Oceanographic Institution in Massachusetts, proved to be pivotal in defining her scientific career. "I happened to be in the right place at the right time," she says.

Researchers were finally finding microorganisms living in the methane seeps, and some indeed appeared to be eating methane. Hinrichs was studying lipids, a class of molecules that includes fat, in samples of archaea from methane-seep mud. He discovered that some of these lipids didn't have as much carbon-13 as they ought to have. (The usual form of carbon, carbon-12, has six protons and six neutrons, while carbon-13, which accounts for about 1 percent of the total carbon on Earth, has an extra neutron.) The only way that the archaea could have such a dearth of carbon-13 is if the microbes were getting their carbon from methane, whose carbon atom is almost always of the carbon-12 variety.

There were other clues as well, Orphan says. Tori Hoehler, now at the NASA Ames

Right: These festive blobs are clusters of microorganisms. The methane-eating archaea are tagged with a fluorescent protein to glow red, and the sulfate-reducing bacteria are tagged to glow green.

Below: The researchers explore the site of a whale carcass via remote-controlled robot.



Research Center, proposed that, given the right conditions, maybe organisms could eat methane with the help of sulfate. Some archaea were known to produce methane, and there were hints that perhaps the reverse process—i.e., methane consumption—was also practical.

In addition to the low-carbon-13 lipids, Hinrich and Orphan found DNA that was closely related to those of the methane-producing archaea. The clincher came in 2001, when Orphan, along with Christopher House at Penn State, Hinrichs, Kevin McKeegan at UCLA, and DeLong, found carbon-13 depletion directly in the archaeal cells. To make this discovery, the researchers combined two techniques—fluorescence *in situ* hybridization (FISH) and secondary ion mass spectrometry (SIMS), which allowed them to directly identify the microbial cells and their isotopic compositions. "This was the first real, concrete evidence that these organisms with sulfate-reducing bacteria were indeed catalyzing this process," says Orphan.

Since then, the field has flourished, with dozens of groups around the world studying these methane-eating microbes. "The story of anaerobic methane oxidation started with geology and geochemistry," Orphan notes, and the lines between traditional disciplines have blurred. "The whole field of geobiology has blossomed because of these close interactions between geologists, geochemists, and microbiologists." Orphan herself is a prime example. Since she came to Caltech in 2004, her lab has been adapting techniques from geochemistry, molecular biology, and microbiology to try to understand these organisms at the genetic and cellular level.

**DEAD WHALE FALLS**

**Food is scarce at the bottom of the ocean. Organisms forced to live with such bare cupboards rely on manna from above in the form of sinking dead sea creatures. And when a whale falls, it's a buffet, spawning an entire ecosystem of animals like worms and fish, as well as microbes. "You can imagine if a big whale lands in your backyard, you're set for years," says Orphan. In collaboration with Bob Vrijenhoek at the Monterey Bay Aquarium Research Institute, her group has been conducting an extensive study of whale-fall ecosystems since 2003. Because they are self-contained, they provide a perfect natural laboratory to study deep-sea microbial carbon cycling. The team wants to know how carbon flows through the system, and is observing how the microbial communities change as the whale is slowly devoured. One of the surprises they've found is that the whale carcass (if it can be called that; after the larger animals are through with it, all that's left are some bones and baleen—or just a dark spot on the sea floor) provides such a nutrient boost that all sorts of metabolic processes happen, including methane consumption.**

**The first dead whale in the Monterey Bay Canyon was found by accident, Orphan says, but when scientists made it known they were interested in sunken cetaceans, fishermen and the Coast Guard started calling in whenever they saw a whale go belly-up. Now, the team is following five fallen whales at depths ranging from 600 to 2,900 meters.** e&s

**PRYING OPEN THE BLACK BOX**

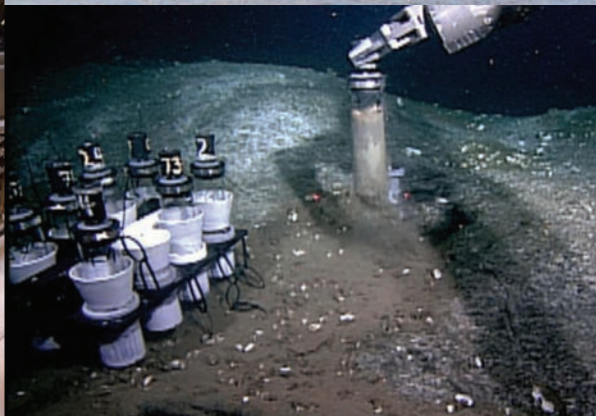
These microbes survive because of a symbiotic partnership in which the archaea oxidize methane and the bacteria reduce sulfate. Because this requires specialized geochemical conditions that are regulated by this partnership, the archaea and bacteria have to be close together. They form clumps of about 100 to 500 cells that resemble bunches of grapes but are only a few microns, or millionths of a meter, in diameter. These clumps, called aggregates, take on a variety of arrangements: sometimes a layer of bacteria encompasses the archaea, and sometimes the two mingle. One of the questions Orphan's lab is trying to answer is how these arrangements influence the rate of methane oxidation and cellular growth.

Three distinct lineages of archaea can eat methane, Orphan explains, and they live with at least two species of sulfate-reducing bacteria, *Desulfosarcina* and *Desulfobulbus*. Together, the symbiosis produces a little energy along with bicarbonate and hydrogen sulfide, which bigger organisms like clams, crabs, shrimp, and tube worms in turn metabolize. The oxidation process isn't a one-step reaction, however, and it remains

Right: Dekas holds one of the tubes used to take sediment samples. Behind her is a robotic sub called the *Doc Ricketts,* which is operated out of the Monterey Bay Aquarium Research Institute. Orphan's lab uses this vehicle to study whale falls.

Far right, top: The *Atlantis* research vessel.

Far right, bottom: *Alvin*'s robot arm takes a sample of the seafloor. After picking up the mud, the arm drops the tube into the empty white canister on the left.



largely a black box.

Scientists do know that the archaea enable methane and water to react and produce an unknown intermediate compound that goes to the bacteria, which complete the job by transferring electrons to the sulfate. But no one knows what this intermediary is—or for that matter, many other details about the process. We aren't even sure how much these organisms depend on each other to live, Orphan says. "We think they require each other for anaerobic methane oxidation, but there are occasions where you find these archaea without bacteria. We're still in the process of seeing if those archaea are active, or if they were at one point attached to a bacterial buddy."

To pry open the black box of the methane-eating microbes, Orphan and her colleagues must go to sea. Methane seeps tend to form at the continental margins, the line on the seafloor where the continental crust stops and the oceanic crust starts. The researchers spend days to weeks aboard ship, using remote-controlled robot submersibles to stick half-meter-long tubes into the seafloor, capturing cylindrical cores of mud teeming with microorganisms. Thin samples are sliced from the cores as soon as they are hauled in, preserving any variations with depth for later analysis.

Orphan often sails on the *Atlantis*, an 84-meter research vessel owned by the Navy and operated by the Woods Hole Oceanographic Institution that can support a crew of 36 for up to two months. And with *Atlantis* comes *Alvin*, a deep-diving, three-person minisub. Built in 1964, *Alvin* has taken thousands of scientists to the ocean depths and in 1966 was used to find a missing hydrogen bomb off the coast of Spain, but its biggest claim to fame may be exploring the wreck of the *Titanic* in 1986.

Inside the compact vehicle—whose interior, Dekas says, isn't much bigger than the front seat of a car—the two passengers are each glued to their own window, directing the pilot where to go. Even though they know the coordinates of some of the methane seeps, pinpointing their exact location can still be a challenge. "When we first got to the bottom, all we could see was this gray, silty, ocean-bottom nothingness," Dekas says of her thousand-meter dive off the coast of Costa Rica last February. "Our first job was to look out the window for organisms that live on the waste products of anaerobic methane oxidation—creatures like clams, tube worms, or a kind of white fuzz on the ground, which would be a sulfide-oxidizing bacterial mat. Once we started to see them, we'd call them out to each other: 'Oh! A bush of tube worms over here!'" A typical dive at the bottom of the ocean lasts about seven hours, which raises the question of restrooms. "They give you a bottle—with an attachment if you're a woman," Dekas answers. "There's no privacy; you become really good friends really quickly."

In 2006, *Alvin* took Orphan down 500 meters to the floor of the Eel River Basin, about 30 kilometers off the coast of Eureka in northern California. It was these samples that led to the discovery that deep-sea methane oxidizers not only curb oceanic methane emissions, but also may play a role in the cycling of nitrogen. "Nitrogen is in DNA and all of your proteins," says Dekas. "It's pretty much an essential element for life." But in its gaseous state, nitrogen takes the form of two atoms sharing electrons in a tight triple bond. You need a lot of energy to break that bond and reduce $N_2$ to a biologically usable form such as ammonia ($NH_3$), a process called nitrogen fixation. In fact, wresting those two nitrogen atoms apart takes about 800 kilojoules per mole, with a mole being about $6.022 \times 10^{23}$ molecules. Since the methane-eating microbes had to

"When we first got to the bottom, all we could see was this gray, silty, ocean-bottom nothingness," Dekas says.


Far left: Posing with *Alvin* are postdoc Burt Thomas (USGS), Orphan, postdoc Jake Bailey, Dekas, Shana Goffredi, and postdoc David Fike.

Leftt: Orphan at the controls of a robotic sub.

subsist on a meager energy budget—the methane oxidation reactions only yield about 40 kilojoules per mole of methane at the seeps—no one thought they could afford to fix nitrogen.

But in 2008, the researchers found genes in the archaea that suggested otherwise. This collaboration consisted of postdoc Annelie Pernthaler, now at the Helmholtz Centre for Environmental Research in Leipzig, Germany; Dekas; C. Titus Brown (PhD '07), then a biology postdoc who is now an assistant professor at Michigan State University; Shana Goffredi, then a senior research fellow and now an assistant professor at Occidental College; Tsegereda Embaye, a technician with the lab; and Orphan.

In order to get to the genomes, the researchers first had to single out the microbial cells from a patch of mud—a task more daunting than retrieving the proverbial needle from the haystack.

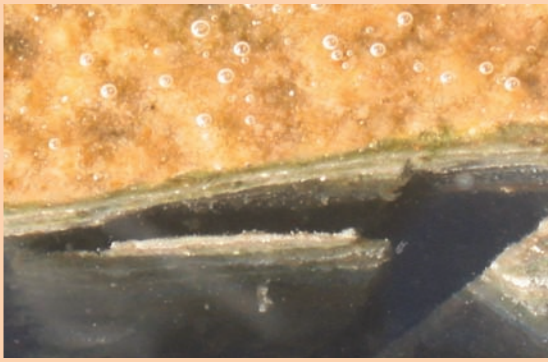
Magnets work well for finding needles, and coincidentally, Orphan's lab developed a Caltech-patented technique called magneto-FISH to find the microbes. (Remember, FISH stands for fluorescence *in situ* hybridization.) The ribosome, the protein-making machine of every species, includes unique molecules of RNA, a one-stranded molecule that is similar to DNA. Both RNA and DNA are made up of a sequence of "bases"—the letters of the genetic alphabet. RNA and DNA can bind to each other by matching letters on the DNA strand with complementary ones on the RNA strand. Thus, you can pick out an RNA strand with a DNA probe—if you know the sequence of the RNA you're looking for, you can design a single-stranded fragment of DNA with the complementary sequence of bases. The probe will then bind to that specific RNA molecule. Attaching a fluorescent molecule to the probe turns it into a marker, illuminating the bound RNA—and, therefore, the cells you want to find. These probes come in several colors, allowing the researchers to distinguish the bacteria from the archaea by their hues.

But you still have to get the bugs out of the mud, and this is where "magneto" comes in. The researchers attach tiny magnetizable beads, about five microns in diameter, to an antibody that targets the fluorescent molecules. The antibodies then bind to the outside of the glowing archaeal cells. Using a magnet, the researchers can then lift the cells out of the muck.

Pernthaler and her colleagues used magneto-FISH on the archaea and found *nif* genes, which were known to encode enzymes needed to fix nitrogen gas. But just because the microbes have the necessary genes to fix nitrogen doesn't mean they actually do so. To find out, Dekas, Orphan, and Rachel Poretsky, a postdoc, incubated the cells for six months in an atmosphere of methane spiced with nitrogen gas made

**MATS OF MICROBES**

**Bacterial mats are layered carpets of bacteria that thrive in extreme environments—salt flats, hot geothermal vents, or ocean bottoms. At several centimeters thick, and sometimes stretching for hundreds of square kilometers, these masses of microbes can be vast. With different species of bacteria in every thin layer, they are also one of the most diverse ecosystems on the planet, Orphan says, and likely covered Earth before the rise of multicellular organisms. Orphan's lab studies the biochemistry and changing abundances of sulfur isotopes in layered mats like this one, taken from the Guerrero Negro saltworks in Baja California Sur. At the top layers of the mats, where sunlight is plentiful, photosynthesis with oxygen occurs. But further down, the microorganisms survive through processes without oxygen. These mats, which look sort of like moldy lasagna, were prevalent early in Earth's history and likely influenced sulfur cycling on a global scale. Like the microbes at methane seeps, these mats show how life endures in unexpected places.** E&S



Right: Layers of a bacterial mat. The orange layer is made of microorganisms—mainly diatoms and cyanobacteria—that use photosynthesis to make energy. The microorganisms that make up the black layer are anaerobic, producing energy by sulfate reduction, fermentation, or other oxygenless processes.



Left: The researchers encounter an octopus as they take samples in the Eel River Basin.

Right: While on a dive, Orphan finds an impressive surprise.

from nitrogen-15. (Like carbon-13, nitrogen-15 is a stable, naturally occurring isotope, making up about 0.36 percent of the world's nitrogen.) The presence of nitrogen-15 in the archaeal cells would therefore show that they were fixing nitrogen.

The team looked for the nitrogen-15 with a technique called nanoscale secondary ion mass spectrometry (nanoSIMS), in which the cells were scanned by a beam of cesium ions. These heavy, high-energy particles blasted the cells into oblivion, and whatever lighter ions bounced back out from the wreckage were collected and identified. The result was a map of the nitrogen-15 distribution in the archaea and their bacterial partners.

When the researchers combined these maps with FISH-generated images of the bacteria-archaea clusters, they saw nitrogen-15 concentrated in the archaeal cells. "That's when we knew that the archaea were able to fix nitrogen, because we could see nitrogen-15 in their biomass," Dekas says. To a lesser degree, nitrogen-15 was also present in the bacterial partner, meaning that the archaea were sharing the valuable nutrient.

To compensate for the energy-intensive process of fixing nitrogen, the microbes slowed their growth. When the organisms were incubated with ammonia, which takes far less energy to break down, they grew about 20 times faster than those forced to fix nitrogen gas.

This discovery, which was published in the October 16, 2009, issue of *Science*, has also shed light on the global nitrogen cycle. Previous attempts to balance the global nitrogen budget had come up short—more nitrogen was being consumed than was being fixed. The archaea at the methane seeps don't fix enough nitrogen to make up the difference, but the fact that they are doing it suggests that other organisms in unexpected places may also be fixing nitrogen, and together, these overlooked sources may be significant. The find also poses the question: what else are these microorganisms capable of?

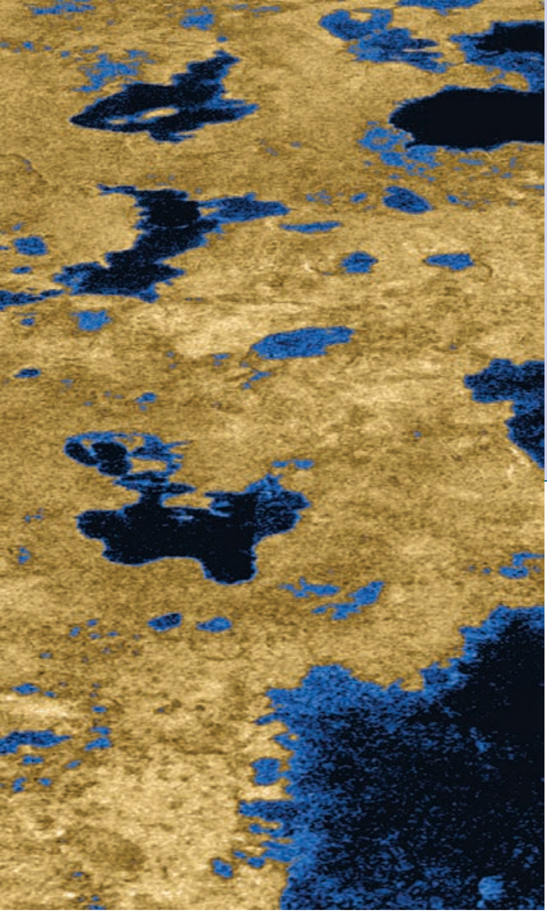
"That's where I see my big contribution," Orphan says. "To be able to do these experiments with living communities and environments that likely have relevance for early Earth ecosystems."

**PUSHING THE BOUNDARIES OF LIFE**

When the microbes eat methane, electrons are transferred from the hydrocarbon to the sulfate. Now Orphan, with Christopher House and graduate student Emily Beal at Penn State, have discovered that the microbes can reduce other compounds as well. Even though sulfate reduction is the best-known way to oxidize methane anaerobically, it's not necessarily the most energetically favorable. Orphan, House, and Beal discovered that manganese and iron also did the trick, describing their findings in the July 10, 2009, issue of *Science*. Carried out to sea by rivers, both metals are abundant: if all of the world's biologically available manganese and iron were used, they could account for perhaps one-quarter of all anaerobic methane oxidation.

Beal incubated sulfate-free methane-seep mud for 10 months with either manganese or iron. The microbes reduced the metals very slowly—likely because as solids, the metals require more time to react. But at 556 kilojoules and 270 kilojoules per mole for manganese and iron, respectively, there's a lot more bang for the buck. It's still unclear which bugs are reducing these metals, but it appears that they're the same archaeal and bacterial symbionts that reduce sulfate, Orphan says, showing that these partnerships are quite versatile.

The fact that these microbes can consume methane several ways means there's a good chance similar organisms existed on the early Earth. Oxygen didn't appear on the planet until less than 2.5 billion years



Left: During a flyby of Titan in 2006, Cassini took this false-color radar image of the moon's surface. In general, brightness corresponds to roughness. The dark areas are very smooth, suggesting they could be lakes or seas.

Below: What was once a whale is now just a smattering of bones and baleen. On the right, crabs crawl on carbonate outcrops.

ago—also through bacteriological activity, as described in *E&S* 2005, No. 4—but the first forms of life appeared some 1.5 billion years earlier. Methane wasn't the only substance around at the time, but it certainly would've been a convenient source of food . . . if it could be eaten.

Studying these bugs, then, is also a way to understand primordial Earth and to unravel the evolution of early life. The present-day organisms that populate methane seeps probably share much of their DNA with those first earthlings. Genetic analyses could trace their evolutionary relationships back to the earliest life forms, Orphan says. And, in some sense, today's seep-dwellers are living fossils whose biochemistry could help researchers better understand ancient environmental conditions and interpret the hazy history embedded in the few old rocks that still exist. "That's where I see my big contribution," she says. "To be able to do these experiments with living communities and environments that likely have relevance for early Earth ecosystems."

The implications might go beyond our planet. The discovery of methane-seep communities and deep-sea hydrothermal vent communities in the 1970s raised some hopes of eventually finding extraterrestrial life. If creatures can thrive in such dark and cold conditions without oxygen, then maybe life could also take hold in even harsher, more alien environments. "For much of the time of life on Earth, life was dominated by anaerobic metabolism," says Dekas. "And if there's life on other planets, then that's probably what's going on there, too."

Could methane be a sign of E.T.? That's one reason why astronomers are fascinated with Saturn's largest moon, Titan, which has a thick nitrogen atmosphere with trace amounts of methane. In 1980 and 1981, the Voyager 1 and 2 spacecraft found evidence of methane lakes on Titan's surface. The ESA's Huygens probe landed on Titan in 2005, and although it didn't splash onto a methane ocean like scientists thought it might, it returned a trove of images showing apparent river flows and channels, as well as finding a constant drizzle of methane rain. But Huygens found no signs of life, nor has the spacecraft that brought it there, JPL's Cassini orbiter. Cassini has, however, mapped countless smooth features that look like lakes and seas—the largest surpassing Lake Superior in area.

Needless to say, scientists have a lot to learn about the archaea and bacteria that together do so much for Earth—laying the foundations for a deep-sea ecosystem, helping to shepherd the global cycling of vital elements, and preventing methane from further warming the planet. "If all bacteria and archaea just stopped functioning, life on Earth would come to an abrupt halt," Dekas says. "I can't think of anything as important as that." E&S

***Victoria Orphan received her BA in aquatic biology in 1994 and her PhD in ecology, evolution, and marine biology in 2001 from UC Santa Barbara. After a stop at NASA Ames Research Center, she became an assistant professor at Caltech in 2004.***

***Her work is supported by the National Science Foundation, the Gordon and Betty Moore Foundation, NASA, and the National Oceanic and Atmospheric Association.***

PICTURE CREDITS
12 — Anne Dekas; 13 — Bill Youngblood; 14 — Jessica Zha and Victoria Orphan; 15-19 — Victoria Orphan; 17 — Chris House; 19 — NASA/JPL/USGS

# The Arrow of Time

You can turn an egg into an omelet, but not an omelet into an egg. Ice cubes melt, but water doesn't spontaneously form ice cubes. These are examples of irreversible processes, which are at the heart of the arrow of time.

Why do we remember the past and not the future? And what does the fact that time moves forward say about the universe?

In *The Curious Case of Benjamin Button*, Brad Pitt's character is born as an old man and grows younger as time passes. This is a clever narrative device, prodding us to think about the course of our lives in a different way. And there is a good reason why reversing the relative direction of time is an effective tool of the imagination: in the actual, nonimaginary world, it never happens. Time has a direction, an arrow pointing from the past to the future, and it has the *same* direction for everybody.

What does it mean to say that time has a direction? Think about watching a movie played in reverse. Generally, it's pretty clear if we are seeing something running the "wrong way" in time. A classic example is a diver and a pool. If the diver dives, and then there is a big splash, followed by waves bouncing around in the water, all is normal. But if we see a pool that starts with waves, which collect into a big splash, in the process lifting a diver up onto the board and becoming perfectly calm, we know something is up: the movie is being played backward.

Certain events in the real world always happen in the same order. It's dive, splash,

by Sean Carroll

waves, never waves, splash, spit out a diver. Take milk and mix it into a cup of black coffee; never take coffee with milk and separate the two liquids. Sequences of this sort are called *irreversible processes*. We are free to imagine that kind of sequence playing out in reverse, but if we actually see it happen, we suspect cinematic trickery rather than a faithful reproduction of reality.

Irreversible processes are at the heart of the arrow of time. Events happen in some sequences, and not in others. Furthermore, this ordering is perfectly consistent, as far as we know, throughout the observable universe. Someday we might find a planet in a distant solar system that contains intelligent life; but nobody suspects that we will find a planet on which the aliens regularly separate (the indigenous equivalents of) milk and coffee with a few casual swirls of a spoon. Why isn't that surprising? It's a big universe out there; things might very well happen in all sorts of sequences. But they don't. For certain kinds of processes—roughly speaking, complicated actions with lots of individual moving parts—there seems to be an allowed order that is somehow built into the very fabric of the world.

The arrow of time, then, is a brute fact about our universe, arguably *the* brute fact about our universe. The fact that things happen in one order and not in the reverse order is deeply ingrained in how we live in the world. Why is it like that?

The answer lies in the concept of *entropy*. Like energy or temperature, entropy tells us something about the particular state of a physical system; specifically, it measures how disorderly the system is. A collection of papers stacked neatly on top of one another has a low entropy; the same collection, scattered haphazardly on a desktop, has a high entropy. The entropy of a cup of coffee along with a separate teaspoon of milk is low, because there is a particular orderly segregation of the molecules into "milk" and "coffee," while the entropy of the two mixed together is comparatively large. All of the irreversible processes that reflect time's arrow—we can turn eggs into omelets but not omelets into eggs, perfume disperses through a room but never collects back into the bottle, ice cubes in water melt but glasses of warm water don't spontaneously form ice cubes—share a common feature: entropy *increases* throughout, as the system progresses from order to disorder. Whenever we disturb the universe, we tend to increase its entropy.

## NATURE'S MOST RELIABLE LAW

The principle underlying irreversible processes is summed up in the second law of thermodynamics: the entropy of an isolated system either remains constant or increases with time. The second law is arguably the most dependable law in all of physics. If you were asked to predict what currently accepted principles of physics would still be considered inviolate a thousand years from now, the second law would be a good bet.

Our modern understanding of entropy was developed in 1877 by Ludwig Boltzmann, who was one of the few physicists at the time who believed in the existence of atoms. Boltzmann realized that when we look at some macroscopic system, we certainly don't keep track of the exact properties of every single atom. (If we have a glass of water in front of us, and someone sneaks in and, say, switches some of the water molecules around without changing the overall temperature and density and so on, we would never notice. There are many different arrangements of particular atoms that are *indistinguishable* from our macroscopic perspective.) And then Boltzmann noticed that low-entropy objects are more delicate with respect to such rearrangements. If you have an egg, and start exchanging bits of the yolk with bits of the egg white, pretty soon you will notice. The situations that we characterize as "low entropy" seem to be easily disturbed by rearranging the atoms within them, while "high-entropy" ones are more robust.

So Boltzmann took the concept of entropy, which had previously been defined as a measure of the uselessness of an object's energy content, and redefined it in terms of atoms: entropy is a measure of the number of particular microscopic arrangements of atoms that appear indistinguishable from a macroscopic perspective.

It would be difficult to overemphasize the importance of this insight. Before Boltzmann, entropy was a phenomenological thermodynamic concept, which followed its own rules (such as the second law). After Boltzmann, the behavior of entropy could be

Listen to a podcast of Sean Carroll discussing time, space, and the universe, and watch him talk about his new book, *From Eternity to Here*.

*derived* from deeper underlying principles. In particular, it suddenly makes perfect sense why entropy tends to increase in an isolated system: because there are more ways to be high entropy than to be low entropy.

At least, that formulation sounds like it makes perfect sense. In fact, it sneaks in a crucial assumption: that we start with a system that has a low entropy. If we start with a system that has a high entropy, we'll be in equilibrium—nothing will happen at all. That word *start* sneaks in an asymmetry in time, by privileging earlier times over later ones. And this line of reasoning takes us all the way back to the low entropy of the Big Bang. For whatever reason, of the many ways we could arrange the constituents of the universe, at early times they were in a very special, low-entropy configuration.

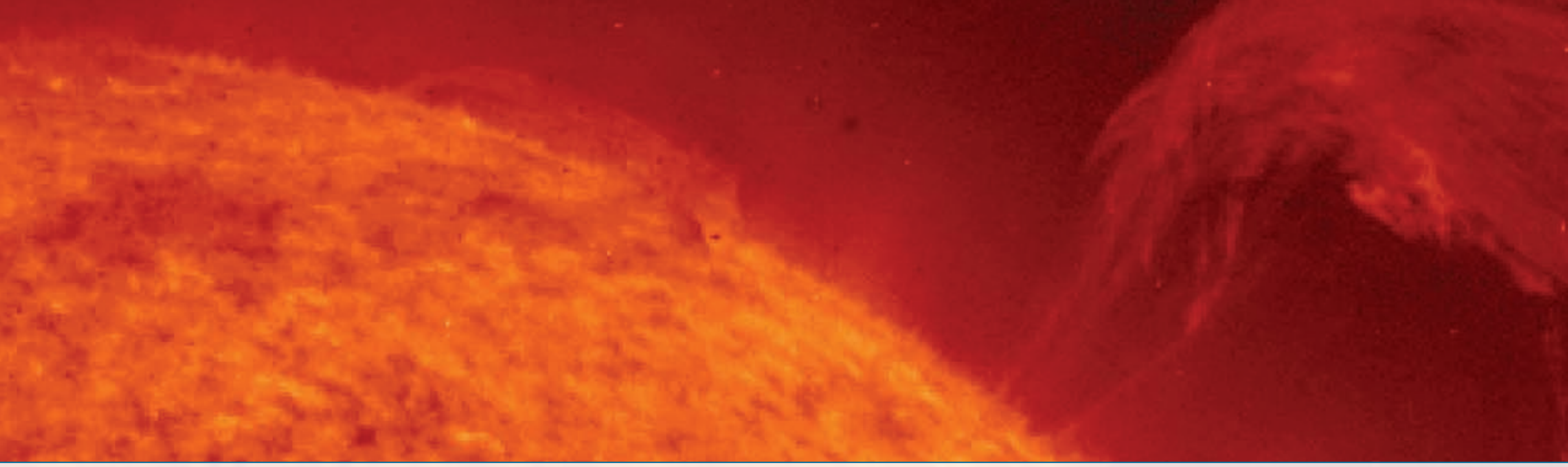
**ENTROPY AND LIFE**

This is all fascinating stuff, at least to physicists. But the ramifications of these ideas go far beyond steam engines and cups of coffee. The arrow of time manifests itself in many different ways—our bodies change as we get older, we remember the past but not the future, effects always follow causes. It turns out that *all* of these phenomena can be traced back to the second law. Entropy, quite literally, makes life possible.

The major source of energy for life on Earth is light from the sun. One consequence of the second law is that heat naturally flows from a hot object (the sun) to a cooler object (Earth). But if that were the end of the story, before too long the two objects would come into equilibrium with each other—they would attain the same temperature. In fact, that is just what would happen if the sun filled our entire sky, rather than describing a disk about one degree across. The result would be an unhappy world indeed. It would be completely inhospitable to the existence of life—not simply because the temperature was high, but because it would be *static*. Nothing would ever change in such a world.

In the real universe, the reason our planet doesn't heat up until it reaches the temperature of the sun is Earth loses heat by radiating it out into space. And the only reason it can do that is that space is much colder than Earth. It is because the sun is a hot spot in a mostly cold sky that Earth doesn't just heat up, but rather can absorb the sun's energy, process it, and radiate it into space. Along the way, of course, entropy increases; a fixed amount of energy in the form of solar radiation has a much lower entropy than the same amount of energy in the form of Earth's radiation into space.

This process, in turn, explains why Earth's biosphere is not a static place. We receive energy from the sun, but it doesn't just heat us up until we reach equilibrium; it's very low-entropy radiation, so we can make use of it and then release it as high-entropy radiation. All of which is only possible because the universe as a whole, and the solar system in particular, has a relatively low entropy at the present time (and an even



lower entropy in the past). If the universe were anywhere near thermal equilibrium, nothing would ever happen.

Nothing good lasts forever. Our universe is a lively place because there is plenty of room for entropy to increase before we hit equilibrium and everything grinds to a halt. It's not a foregone conclusion—entropy might be able to simply grow forever. But alternatively, entropy may reach a maximum value and stop. This scenario is known as the "heat death" of the universe, and was contemplated as long ago as the 1850s, amidst all the exciting theoretical developments in thermodynamics.

To this day, scientists haven't yet determined to anyone's satisfaction whether the universe will continue to evolve forever, or whether it will eventually settle into a placid state of equilibrium.

> The arrow of time isn't just about simple mechanical processes; it's a necessary feature of the existence of life itself.

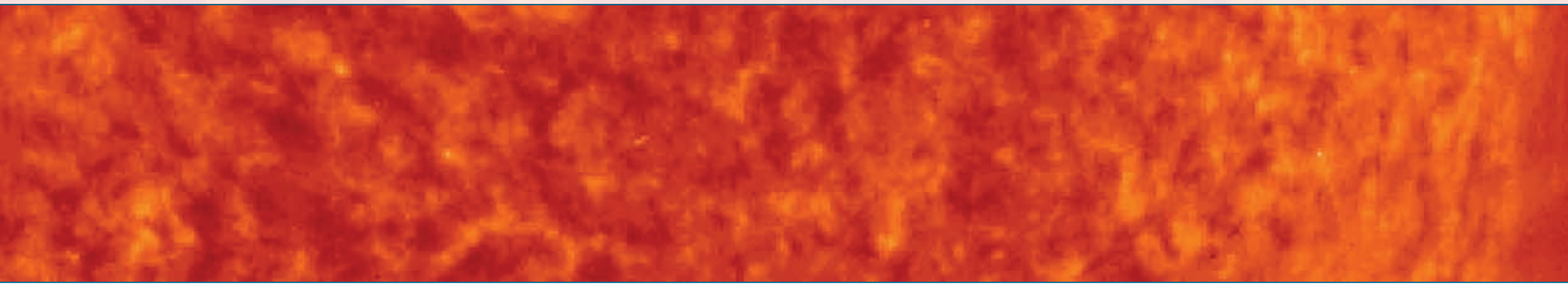
**WHY CAN'T WE REMEMBER THE FUTURE?**

So the arrow of time isn't just about simple mechanical processes; it's a necessary feature of the existence of life itself. But it's also responsible for a deep feature of what it means to be a conscious person: the fact that we remember the past, but not the future. According to the fundamental laws of physics, the past and future are treated on an equal footing; but when it comes to how we perceive the world, they couldn't be more different. We carry in our heads representations of the past, in the form of memories. Concerning the future, we can make predictions, but those predictions have nowhere near the reliability of our memories of the past.

Ultimately, the reason we can form a reliable memory of the past is that the entropy was lower then. In a complicated system like the universe, there are many ways for the underlying constituents to arrange themselves into the form of "you, with a certain memory of the past, plus the rest of the universe." If that's all you know—that you exist right now, with a memory of going to the beach that summer between sixth and seventh grades—you simply don't have enough information to reliably conclude that you really did go to the beach that summer. It turns out to be overwhelmingly more likely that your memory is just a random fluctuation, like the air in a room spontaneously congregating over on one side. To make sense of your memories, you need to assume as well that the universe was ordered in a certain way—that the entropy was lower in the past.

Imagine that you are walking down the street, and on the sidewalk you notice a broken egg that appears as though it hasn't been sitting outside for very long. Our presumption of a low-entropy past allows us to say with an extremely high degree of certainty that not long ago there must have been an unbroken egg, which someone dropped. Since, as far as the future is concerned, we have no reason to suspect that entropy will decrease, there's not much we can say about the future of the egg—too many possibilities are open. Maybe it will stay there and grow moldy, maybe someone will clean it up, maybe a dog will come by and eat it. (It's unlikely that it will spontaneously reassemble itself into an unbroken egg, but, strictly speaking, that's among the possibilities.) That egg on the sidewalk is like a memory in your brain—it's a record of a prior event, but only if we assume a low-entropy boundary condition in the past.

We also distinguish past from future through the relationship between cause and effect: namely, the causes come first (earlier in time), and then come the effects. Think of the diver splashing into the pool—the splash always comes after the dive. According to



If you know the exact state of the universe, and all of the laws of physics, the future as well as the past is rigidly determined beyond John Calvin's wildest dreams of predestination.

the microscopic laws of physics, however, it is possible to arrange all of the molecules in the water (and in the air around the pool, through which the sound of the splash travels) to precisely "unsplash" and eject the diver from the pool. To do this would require an unimaginably delicate choice of the position and velocity of every single one of those atoms—if you pick a random splashy configuration, there is almost no chance that the microscopic forces at work will correctly conspire to spit out the diver.

In other words, part of the distinction we draw between "effects" and "causes" is that "effects" generally involve an increase in entropy. If two billiard balls collide and go their separate ways, the entropy remains constant, and neither ball deserves to be singled out as the cause of the interaction. But if you hit the cue ball into a stationary collection of racked balls on the break (provoking a noticeable increase in entropy), you and I would say "the cue ball caused the break"—even though the laws of physics treat all of the balls perfectly equally.

**THE ART OF THE POSSIBLE**

Because we live in a universe with a pronounced arrow of time, we treat the past and future not just as different from a practical perspective, but as deeply and fundamentally different things. The past has already happened, while the future is still up for grabs in some sense—we can sketch out alternative possibilities, but we don't know which one is real. More particularly, when it comes to the past, we have recourse to memories and records of what happened. Our records may have varying degrees of reliability, but they fix the actuality of the past in a way that isn't available when we contemplate the future.

Think of it this way: A loved one says, "I think we should change our vacation plans for next year. Instead of going to Cancún, let's be adventurous and go to Rio." You may or may not go along with the plan, but the strategy, should you choose to implement it, isn't that hard to work out: you change plane reservations, book a new hotel, and so forth. But if your loved one says, "I think we should change our vacation plans for last year. Instead of having gone to Paris, let's have been adventurous and have gone to Istanbul," your strategy would be very different—you'd think about taking him or her to the doctor, not rearranging your past travel plans. The past is gone, it's in the books, there's no way we can set about changing it. So it makes perfect sense to us to treat the past and future on completely differently.

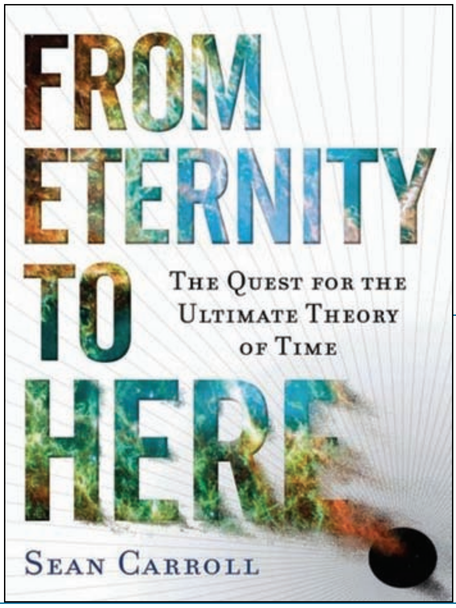
That distinction between the fixedness of the past and the malleability of the future is nowhere to be found in the known laws of physics. The deep-down microscopic rules of nature run equally well forward or backward in time from any given situation. If you know the exact state of the universe, and all of the laws of physics, the future as well as the past is rigidly determined beyond John Calvin's wildest dreams of predestination.

The way to reconcile these beliefs—the past is once-and-for-all fixed, while the future can be changed, but the fundamental laws of physics are reversible—ultimately comes down to entropy. If we knew the precise state of every particle in the universe, we could deduce the future as well as the past. But we don't; we know something about the universe's macroscopic characteristics, plus a few details here and there. With that information, we can predict certain broad-scale phenomena (the sun will rise tomorrow), but our knowledge is compatible with a wide spectrum of specific future occurrences. When it comes to the past, however, we have at our disposal our knowledge of the current macroscopic state of the universe, *plus* the fact that the early universe began in a low-entropy state. That one extra bit of information, known simply as the "past hypothesis," gives us enormous leverage when it comes to reconstructing the past from the present.

The punch line is that our notion of *free will*, the ability to change the future by making choices in a way that is not available to us as far as the past is concerned, is only possible because the past has a low entropy and the future has a high entropy. The future seems open to us, while the past seems closed, even though the laws of physics treat them on an equal footing.

The major lesson of this overview of entropy and the arrow of time should be clear: the existence of the arrow of time is both a profound feature of the physical universe, and a pervasive ingredient of our everyday lives. It's a bit embarrassing, frankly, that with all of the progress made by modern physics and cosmology, we still don't have a final answer for why the universe exhibits such a profound asymmetry in time. I'm embarrassed, at any rate; but every crisis is an opportunity, and by thinking about entropy we might learn something important about the universe. e&s

***Sean Carroll* is a Senior Research Associate in Physics. He received his BS in astronomy and astrophysics from Villanova in 1988 and his PhD from Harvard in 1993. He was then a postdoctoral researcher at the Center for Theoretical Physics at MIT and at the Institute for Theoretical Physics at UC Santa Barbara. Just prior to coming to Caltech in 2006, he was on the faculty at the University of Chicago. This article was adapted from chapter two of his most recent book, *From Eternity to Here: The Quest for the Ultimate Theory of Time*, which explores entropy, the arrow of time, the origin of the universe, and the implication that we live in a multiverse. Carroll is also a regular contributor to the blog *Cosmic Variance*.***




PICTURE CREDITS
20-21 — Doug Cummings; 22-23 — ESA/NASA/SOHO; 24 — Bob Paz

# The Light and Sound Fantastic

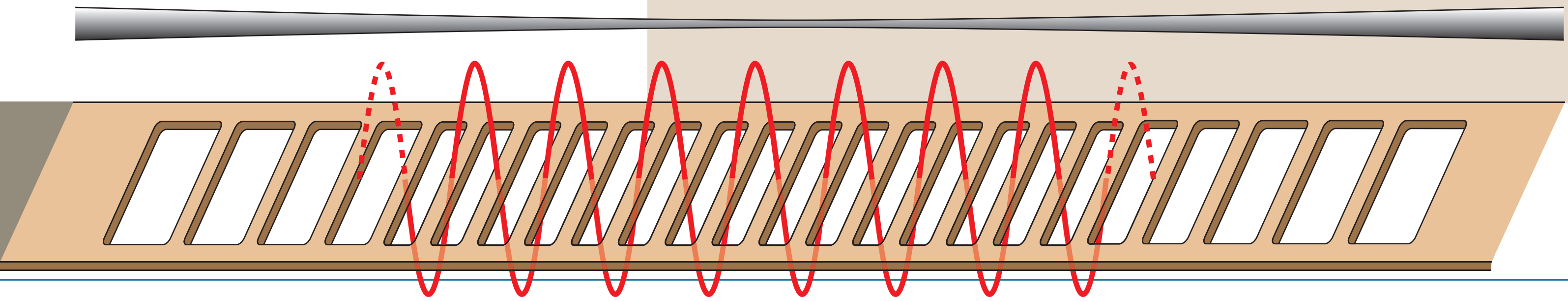
By Douglas L. Smith

A "dabbling" in quantum mechanics leads to a marriage of sound and light on a chip. This could open the door to using sound energy in ways we can't even imagine yet.

Self-styled psychic Uri Geller "bends" spoons with his mind. Associate Professor of Applied Physics Oskar Painter (MS '95, PhD '01) bends silicon with light. In both cases, concentration is the key. Painter's light is trapped in a nanoresonator—a set of tiny spaces each only half the light's wavelength long. Each photon rattles around for a billionth of a second or so, bouncing back and forth some million times in the process.

Trapping light is nothing new, but these cages are so insubstantial that the photons' gentle push makes them flex—vibrate, in fact. They ring, they buzz, they hum, and although this sound is not audible, it is indeed a sound—packets of sonic energy, or pho*n*ons. In fact, converting the photons into phonons—and phonons back to photons again—is as easy as penciling an "n" in over the "t."

Below: Photons can only run along the bridge for as far as their wavelength matches the planks' spacing. The optical fiber taper is in the background.
Opposite: Grad student Matt Eichenfield aligns a microchip with the optical fiber at the test station.



"What is new here is the ability to manipulate sound in a circuit with the same level of control, and in almost the same way, that we manipulate light or electrons," says Painter's collaborator Kerry Vahala (BS '80, MS '81, PhD '85), the Jenkins Professor of Information Science and Technology and professor of applied physics. "It helps to level the playing field for these three different particles—electrons, photons, and phonons." In other words, the door is now open to using all three information carriers on the same piece of silicon, swapping between them as best suits your purpose. Says Painter, "All three can live on the surface of a microchip and can be connected, much like wires can, in your microelectronic circuit."

Any such circuit's phononic components would not be digital, at least not yet, but that's OK. Says Vahala, "In the beginning, electronics were entirely analog. Analog components like oscillators and amplifiers are still vital to modern radio, microwave, and lightwave communications. In fiber-optic systems, lasers provide an electronic-to-optical translator so that digital signals are transmitted through an essentially analog optical system. And now we've created a translator that can shift sound into coherent light, and light into coherent sound."

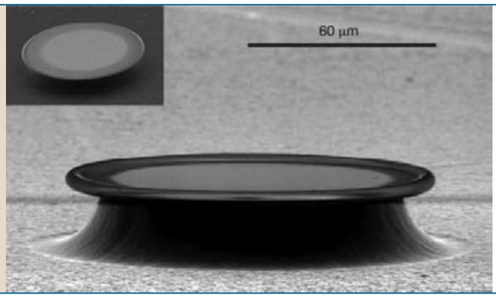
This translator, properly called an optomechanical crystal, looks somewhat like the uninviting rope bridge in an Indiana Jones movie . . . while it still has all its floorboards, *before* anyone sets foot on it. The bridge spans what is essentially a bottomless chasm in the microchip, with the spacing between the 16 floorboards at the midpoint of the bridge being one-half the wavelength of the light to be trapped. The floorboards get farther apart on either side of this zone as you move toward the safety of the banks, a mirror-mimicking design that keeps the light confined at midspan. Photons run with a fixed stride—their wavelength—and if the available footing doesn't match their pace, they have to turn back. Thus no light leaves the bridge; furthermore, none creeps in from the silicon banks on either side.

Which brings us to the question of how the light gets into the bridge in the first place. Just after getting his PhD in 2001, Painter was briefly a postdoc in Vahala's lab. At the time, Vahala's group was beginning to make tiny doughnut-shaped optical resonators on chips—little rings of silicon around which photons could race. The question arose of how to feed in the light, and Vahala recalled a possible technique that had been briefly described in a 1997 paper by a group led by Philip Russell, then at the University of Bath. "Oskar was deeply involved in perfecting this optical taper technology here at Caltech," says Vahala.

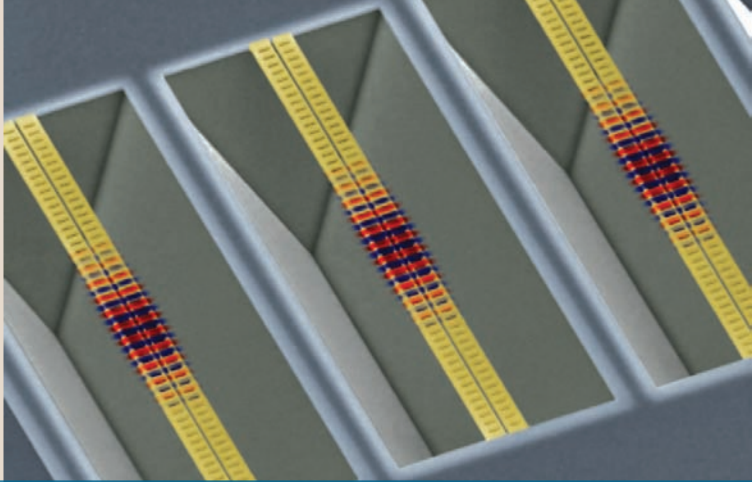
The optical taper is simplicity itself. Take a standard fiber-optic line some 125 microns (millionths of a meter) thick, heat it in a hydrogen flame so as not to affect the glass chemically, and stretch it thin, thin, thin until it's only about one micron in diameter. Says Vahala, "It's so narrow you can literally think of the light as being pushed out of the fiber." The light's electromagnetic field extends slightly beyond the confines of the glass, leaking out like water from an old, overpressurized garden hose that begins to split along its length. "About one percent of the light can't fit through the pipe, so to speak," Vahala continues, "so there's a little bit of optical energy available in the air outside the glass." If you put the taper parallel to, and within about a micron of, your resonator, some of that "outside" light can be siphoned off into the resonator. It doesn't take much, says Vahala. "A very tiny fraction of a percent is enough. It's like giving a very tiny nudge to a pendulum at the same point in its swing every time—eventually you get a huge effect."

The next step came around 2004, when the doughnut-resonator studies took an unforeseen turn. As the photons chased their tails around the ring, the doughnut was found to actually expand and contract slightly. It turned out that the photons were transferring energy to the doughnut, causing it to vibrate. These oscillations, in turn, imprinted themselves onto the light leaking from the resonator back into the taper. (The light bleeds out of the resonator for the same reason it leaks out of the taper—the resonator is too small to completely contain the electromagnetic field.) Meanwhile, Painter, by then an assistant professor, was mining the vein he had started as a PhD student—trapping and manipulating light on a chip using micromachined structures called photonic crystals. Painter approached Vahala about applying the same methods to engineer a mechanical system that would oscillate with the oscillating light.

One of Vahala's original optical resonators sits on its silicon pedestal. The light is trapped in the bulge that circles the rim, and the out-of-focus horizontal gray line in the foreground is the fiber-optic taper. The scale bar is 60 microns, or millionths of a meter. (From D. K. Armani et al., *Nature*, Vol. 421, pp. 925–928, Feb. 27, 2003. Reprinted by permission from Macmillan Publishers Ltd.)



A rendering of three optical zippers on a microchip. (Fiber tapers not shown for clarity.) Each bridge is about 30 microns long and one micron wide. The gap down the middle is 120 nanometers, or billionths of a meter. The red and blue bands show the light's phase. When the two bridges are in phase, as seen here, they are pulled toward each other and the zipper zips up. When the light is out of phase, the bridges repel each other and the zipper unzips.



**THE BRIDGES OF MATTHEW EICHENFIELD**

Painter's original notion was simply to make the bridge sway, as if it were being buffeted by a high wind. The collaboration's first project, built by grad student Matt Eichenfield (MS '07) and postdoc Ryan Camacho, consisted of two parallel silicon-nitride bridges—two independent resonators—spaced 120 nanometers, or billionths of a meter, apart. Simulations by grad student Jasper Chan had shown that the bridges should shove each other sideways as a consequence of the trapped light's tight confinement. Again, some of the electromagnetic field leaks out, but now the field's intensity falls off so rapidly that the gradient itself exerts a perceptible force on the other bridge.

As Vahala explains, "If you scanned a light meter across a tightly focused laser beam, the light intensity would be seen to rise and then fall again. And if a small particle of glass passed through that little spot, there would be a very weak force exerted by the light field that would actually pull the glass in toward the center of the spot. The higher the intensity, the deeper the potential well." (Biologists use lasers this way to shove DNA strands, viruses, and even living cells around with so-called optical tweezers.)

Chan's simulations showed that the two bridges could sway in sync with each other, bending in the same direction at the same time, or they could move in opposite directions, spreading apart like a zipper unzipping. The device was thus promptly dubbed the "optical zipper," a much catchier name than the usual "optomechanical cavity." The zipper worked as predicted, and Eichenfield was the lead author on the *Nature* paper that announced it on May 28, 2009.

As the bridges moved, the width of the gap between them changed, and the properties of the light field in that cavity changed as well. The resulting pulses, one per sway, could be read off by measuring the light coming out of the taper lying suspended alongside the bridges—very much the way the whole field had started four years earlier—and the dribble of light directly revealed the zipper's changing position.

In turn, the constantly changing field in the gap affected the zipper's motion. Says Camacho, "Imagine you pluck a note on a guitar, and then you shine a laser pointer on the string and it goes from a low A to a high A. Or vice versa. We can get a factor of 10 increase or decrease in the vibrational frequency." Under the right conditions, says Painter, a single photon can produce a force 15 times stronger than gravity. If that force is 180 degrees out of phase with the motion, it in effect tightens the string, making it vibrate at a much higher frequency. Says Painter, "One structure we studied naturally resonated at 8 megahertz. When we sent in 100 microwatts of optical power, which produces something on the order of 1,000 stored photons in the cavity, the resonance frequency increased to 19 megahertz—simply because of the light. It no longer behaved like silicon nitride, which is pretty stiff stuff already, but as if it were stiffer than diamond. We can cause the zipper to vibrate at a frequency that is predominantly determined by the light field, almost independent of the material it's made out of."

**BRING ON DA NOISE**

So the zipper is twanging like a guitar string, but that's not the only sound it's making. Says Painter, "About a year ago, Matt realized that there's a second set of mechanical vibrations that we should look at." It turns out that the individual floorboards also have vibrational modes. Sound gets trapped in the floorboards for the same reason that light gets trapped in the spaces between them—as the floorboards get farther apart, their spacing no longer matches the sound's wavelength, trapping the energy. And because the trapped phonons and photons have the same wavelength, the two sets of waves can swap energy back and forth—even though their frequencies are quite different.

Since these vibrations are purely internal affairs, you don't need a zipper to study them. Eichenfield, Chan, and Camacho built a bunch of lone bridges, and the successful interconversion of photons to phonons and back again was worth a second *Nature* paper (published on November 5, 2009), and a PhD thesis for Eichenfield. The phonons in these bridges vibrated at around two gigahertz—in the microwave range, in terms of electromagnetic frequencies—while the photons were at 200 terahertz, or just to the infrared of visible light.

“Imagine you pluck a note on a guitar, and then you shine a laser pointer on the string and it goes from a low A to a high A. Or vice versa.”

As it happens, coupling sound waves to microwaves is already big business in the telecommunications field. Your cell phone plucks your conversation out of the unremitting babble in that very crowded region of the electromagnetic spectrum by using a gadget called an acoustic delay filter. The phone’s internal antenna is a thin metal sheet deposited on a piezoelectric crystal, which is a material that expands or contracts when an electric field is applied to it. The electromagnetic waves in the antenna set up corresponding ripples in the crystal that propagate along its surface in all directions. Waveguides split these surface waves, sending them along numerous routes of various lengths. When the sound waves get recombined at the end of their journeys, the differences between their arrival times allow the phone to discriminate between the jammed-together frequencies in the original microwave signal, tuning in to the one band carrying your call to the exclusion of all others.

What makes this possible is that the sound waves in the crystal propagate 10,000 times more slowly than the electromagnetic waves in the metal, so a tiny difference in the phonons’ path length will have a noticeable effect on their arrival times. If you sent the original microwaves racing down those same paths, they’d still show up neck-and-neck at the finish line. Says Painter, “Your phone has a large number of these little filters built into it. People have wanted to do the same thing with light for a long time.”

Like the airways, the pathways in fiber-optic cables are limited commodities, and there is no end in sight to the steadily increasing demand for finer and finer slices of the bandwidth. An optical delay could relieve data congestion, enable very narrow-band filters, and in general let us cram a lot more data streams into each fiber, says Vahala. “There’s an intense interest in trying to achieve long delays in a tiny amount of space—long being hundreds of nanoseconds, which doesn’t sound like much, but if you think of it in terms of propagation distance, a foot per nanosecond for light, you’re talking about hundreds of feet. This is a task that’s not particularly well suited for electronics, as it turns out. One of the approaches for the last couple of decades has been based on taking optical fiber, spooling it up tight—literally on little fishing-line spools—and then very carefully trimming it to length. And I mean *very* carefully—in some applications controlled to tens of microns.” Says Camacho, “The idea is to be able to use photons over long distances, and phonons over chip distances, and then have a box that converts them back and forth on the chip.”

Controlling the delay lengths for phonons on a microchip is much easier—not only

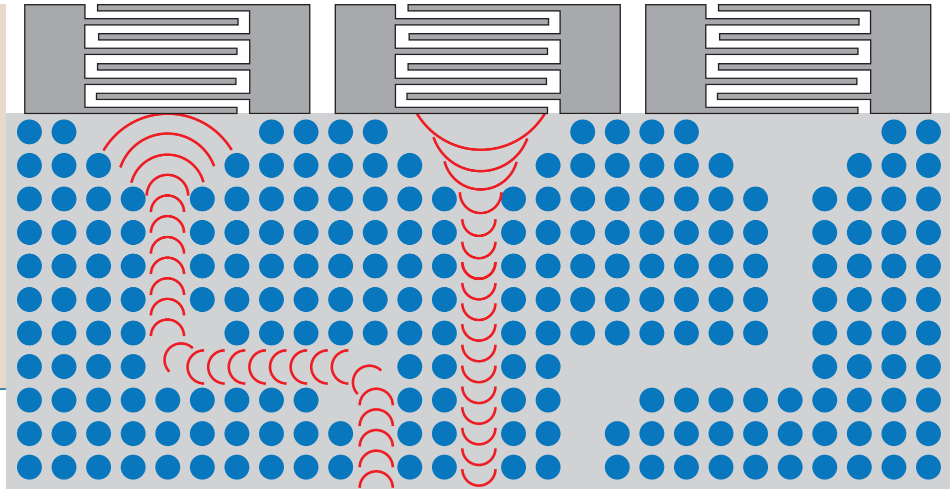
The pinch mode has the lowest vibrational energy. Here the bridge’s floorboards flex toward and away from their neighbors in pairs, like a series of parentheses: ()()()().

The accordion mode has an intermediate amount of energy. Here the floorboards bend toward and away from the center as if they were nested parentheses, like this: (((())))).

The highest-energy mode is the breathing mode, in which the floorboards expand and contract along their lengths, causing the side beams to bow outward and then inward.

**PICTURE CREDITS**
26, 32 — Bill Youngblood; 27, 30 — Doug Cummings; 28, 31 — Jasper Chan and Matt Eichenfield; 29 — Matt Eichenfield and Jasper Chan

In today's phononic chip prototypes, piezoelectric combs (dark gray) send and receive sound waves (red) that travel through the chip (light gray) via waveguides defined by patterns of holes (blue). The circuitry in the chip is not drawn to scale—if it had been, the holes would be too small to see. (Adapted from Olsson and El-Kady, *Measurement Science and Technology*, Vol. 20, 012002, 2009, with permission of IOP Publishing Ltd.)



because they travel so much more slowly, but because all you have to do, in the simplest scenario, is drill tiny, precisely spaced holes in the chip using standard industrial techniques. The holes, when laid out in the proper pattern, act as the waveguide by defining the walls of the "pipe" that confines the sound waves. Quite elaborate sonic plumbing systems can be created this way, at least in principle. Says Eichenfield, "Phonons don't leak out into the world. They are confined to the surface of the chip, so they stay where you put them. And phonons can go around 90-degree corners, which photons can't do."

They're so big that they perturb the system, says Eichenfield. "You've got to create this giant structure, lay down metal, and so on. But an optomechanical crystal transduces itself. You don't have to put anything extra on the chip."

Eichenfield envisions a moat carved around the portion of the chip containing the photonic circuit, defining its boundaries, and with bridges across the moat at the exits and entrances to the waveguides—sort of

them, producing an intense, coherent beam of light that exits through the leaky mirror. Similarly, a properly spaced set of floorboards on one side of the nanoresonator will act as a partial reflector. Pumping energy into the bridge from its adjoining taper will send a beam of phonons into the chip. And once on the chip, the phonons could be mixed and manipulated alongside photons and electrons.

Like Schrödinger's much-abused cat, who is neither alive nor dead but both together until you open its box to look, the bridge is nowhere in particular until you observe it.

The problem has been the transducers—the devices that get the sound into and out of the waveguides. The state of the art is an "interdigitated transducer," which is essentially two sets of tiny metal-coated piezoelectric combs with their teeth interlocked. Again, the piezoelectric teeth convert sound waves into electrical impulses and vice versa. But the combs are huge, in chip-making terms—200 by 800 microns or more.

like a simplified map of the island of Manhattan. A bridge could act as a receiver that collects phonons from the circuit and turns them into light to be sent to the outside world by the adjoining fiber-optic taper, or the bridge could be a phonon "laser" aimed into the circuit. In a laser, trapped photons bounce between two mirrors, one of which is a little bit leaky. As the photons slosh back and forth, they entice other photons to join

**QUANTUM BRIDGES COOLING DOWN**

There are plenty of potential applications beyond signal processing. A bridge could be used as a molecule-specific zeptogram-scale mass sensor, for example. A zeptogram has nothing to do with the Marx Brothers; instead, the prefix comes from the Latin *septem*, "seven." A zeptogram is $10^{-21}$ grams—the mass range of a smallish protein, such as a molecule of hemoglobin A. To detect your quarry in this case, you'd simply paint the bridge with a hemoglobin-specific binding agent and sit back. When a passing hemoglobin got snared, the added mass would slow the pinch mode's acoustic frequency just a shade—by some 700 parts in two billion. And as the motion changed, the light field would change, allowing you to "watch" the protein attach and detach itself on a microsecond timescale. This could be a very handy tool for studying the molecular ballets involved in such things as a drug interacting with its receptor, or a protein catalyzing a biological process.

While Painter's lab hasn't tried this yet, in 2006 a zeptogram-scale sensor based on a vibrating nanobeam—a bridge without the holes, basically—was developed at Caltech's Kavli Nanoscience Institute (KNI) by grad student Ya-Tang Yang (MS '00, PhD '06), then-staff member Carlo Callegari, grad student (now staff scientist) Philip Feng (MS '01, PhD '07), Kamil Ekinci of Boston University (a former Caltech postdoc), and Michael Roukes, professor of physics, applied physics, and bioengineering and the KNI's codirector.

These bridges could also find uses in fundamental physics experiments—they are so close to being immaterial that they can be made to behave quantum mechanically. In the quantum world, you can accurately measure either position or momentum, but not both. If the bridge were to be cooled to its lowest possible energy state, there would remain what's called the zero-point motion—"a little wave packet that describes the 'fuzziness' of the structure, so to speak," says Painter. "In our case, it's on the order of a few femtometers," or quadrillionths of a meter. Like Schrödinger's much-abused cat, who is neither alive nor dead but both together until you open its box to look, the bridge is nowhere in particular until you observe it. Says Painter, "It's in a whole distribution of positions all at once, and then if we measured it, we'd cause it to be in one position only—it's deflected or it's not, or it has a certain amount of vibrational energy or it doesn't. And what's fun about these mechanical systems is that you really can ask the question, 'Well, was the beam here, or was it over there?' I mean, that's a very simple question."

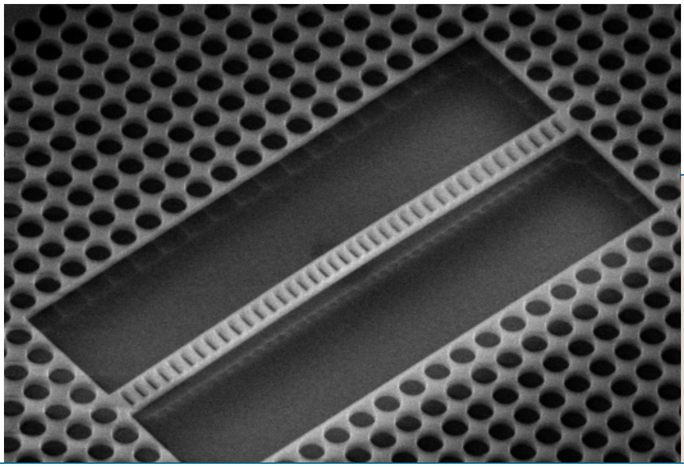
A couple of dozen research groups around the world are racing toward the quantum ground state. The current leader is Caltech's Keith Schwab, associate professor of applied physics, who with colleagues at Cornell, the University of Maryland, and McGill University has cooled a different nanobeam design to the point where, says his web page, "we expect the device to spend 21 percent of its time in the quantum ground state." (The work appears in a *Nature* electronic preprint dated July 16, 2009, linked to his publications page.)

Easy access to the quantum world could lead to uses in quantum communication, which offers the potential for providing a secure, uneavesdroppable way of transmitting information, and quantum computing—manipulating the quantum states of photons and atoms to store and process information in ways that present-day computers simply can't. In 2006, H. Jeff Kimble, Caltech's Valentine Professor and professor of physics, Vahala, and a slew of grad students and postdocs collaborated on a project to see if photons—and thus potentially information—could be transferred from one of Vahala's ring resonators across

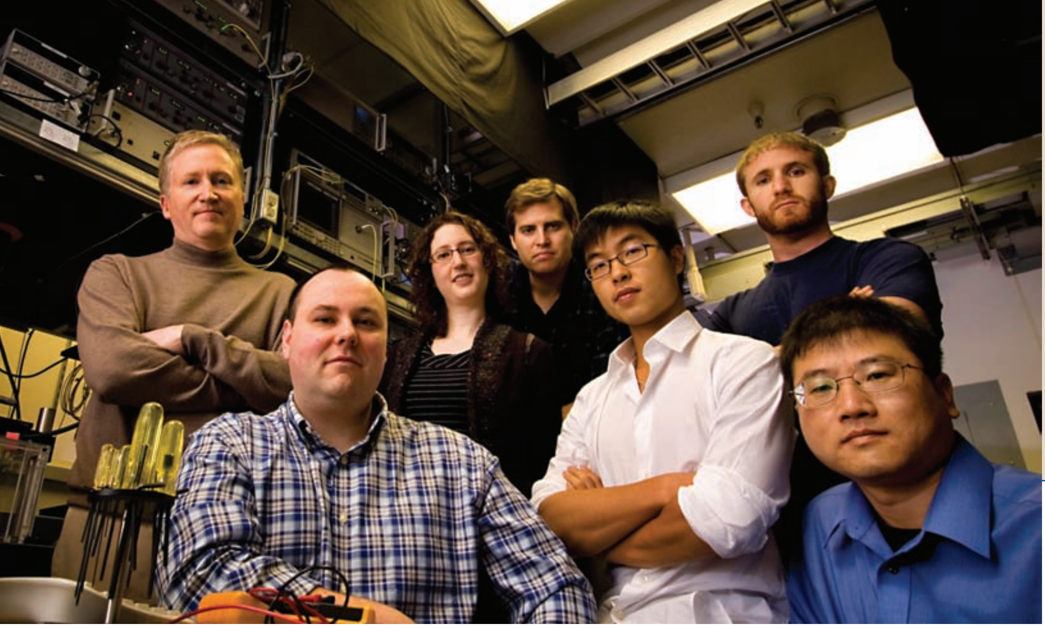
**THE KAVLI NANOSCIENCE INSTITUTE**

**Painter's and Vahala's labs make their nanodevices in the Kavli Nanoscience Institute's clean rooms in the subbasement of the Steele Laboratory of Electrical Sciences. The KNI has a state-of-the-art set of all the standard chipmaking and test equipment you'd find in an integrated circuit factory, available to the entire Caltech/JPL community. "It's a very important facility for our work," says Painter. "We couldn't have done any of this without it." His group uses the Class 1,000 suite, meaning that there are fewer than 1,000 particles of 0.5 microns or larger per cubic foot of air. For comparison, typical Pasadena air can have 1,000,000 particles that size per cubic foot. (There's also a Class 100 suite, but, he says, "It's not like we're doing 50 lithography steps on a 12-inch-diameter wafer, and every single element has to work.")**

**The KNI was founded in 2004, and it provides equipment and expertise to support researchers in fields ranging from biotechnology to astrophysics. Besides Roukes, the KNI's other codirector is Painter's old prof, Axel Scherer, the Neches Professor of Electrical Engineering, Applied Physics, and Physics.** e&s



An electron micrograph of an optomechanical crystal. In this case, the holes in the silicon supporting the bridge act as insulation, keeping the outside world from interacting with the system. Such a setup could be used for quantum-mechanical studies.



From left: Vahala, Painter, grad student Jessie Rosenberg, Camacho, Chan, Eichenfield, and postdoc Qiang Lin. Rosenberg and Lin study a different class of optical resonators that look like two of Vahala's rings stacked on top of each other with a gap in between.

some 45 nanometers of empty space to a passing cesium atom. (Cesium atoms are to quantum-physics experiments what fruit flies are to genetics experiments.)

In these experiments, postdocs Takao Aoki, Barak Dayan, Warwick Bowen, Andrew Parker, and Tobias Kippenberg (MS '00, PhD '04) and grad student Elizabeth Wilcut (PhD '10) would suspend over the resonators a cloud of a few million cesium atoms cooled to 10 millionths of a degree above absolute zero—the temperature at which all atomic vibrations cease. Every five seconds, the lasers responsible for levitating the cloud would be shut off, and a few dozen cesium atoms would plunge like tiny apples through the electromagnetic field generated by the light circulating in the rings. As the atoms fell, each one could trade a quantum of energy with the light field and, indeed, they did.

Painter foresees using the zipper's gap to catch atoms or even larger things, such as "a little nanoparticle of glass, for instance, of maybe a billion atoms. We could use the light fields to trap it and cause it to vibrate at any particular frequency. We could potentially cool it to the quantum-mechanical ground state very easily, even at room temperature, because it's got no tethering to the outside world. The only thing it couples to is the light field." He adds, "We can couple various different quantum systems to each other and to electronics, and my vision is that this will be a beautiful bridge that will enable a lot more quantum technologies.

"This field of reseach is blossoming at Caltech," Painter continues, "because we have a number of groups bringing together expertise in areas as diverse as nanofabrication and quantum optics. I think the next few years are going to be tremendously productive. I find it fascinating that we can work in areas that touch upon fundamental quantum physics and at the same time have a real impact on engineering and technology."

As just one example of the potential impact, "we've basically built a phonon laser on a chip," says Eichenfield. "What's it good for? That's like asking what a laser is good for. When Charles Townes [PhD '39, Nobel laureate in physics, 1964] invented the maser, which eventually gave birth to the laser, he didn't envision CDs, or supermarket checkout scanners, or using them to write your name on the diamond in an engagement ring. We're in the ruby-laser era with these. We can make $10^{12}$ phonons per second with a frequency-to-linewidth ratio [the measure of a laser's coherency] of a few million. That's about where lasers started. In a few years, we'll be putting out phonons on a level with commercial lasers." Adds Camacho, "Optomechanical crystals are a really juicy subject that nobody saw coming. I remember the day when Matt came to my office and showed me his simulations on his laptop, and said, 'Hey, look—the vibrational modes are *right there*. Just sitting there.' It's just really cool, and it's been much easier than we anticipated." Chimes in Eichenfield, "It uses standard fabrication techniques and it operates at microwave frequencies, which makes it technologically relevant, because that's what the telecommunications industry uses. So we've basically produced a whole new technology out of our dabblings in quantum mechanics." e&s

***Oskar Painter earned his BS from the University of British Columbia in 1994, and his MS (1995) and PhD (2001) from Caltech, all in electrical engineering. He ventured briefly into the outside world to cofound a company that applies photonics to telecommunications before becoming an assistant professor in 2002.***

***Kerry Vahala arrived at Caltech as a sophomore in 1977, and has been here ever since. He got his BS in applied physics in 1980 and his PhD in '85, with a small detour for an MS in electrical engineering in '81. He became an assistant professor in 1986 and the Jenkins Professor in 2002.***

***The work was funded by grants from the Defense Advanced Research Projects Agency and the National Science Foundation.***

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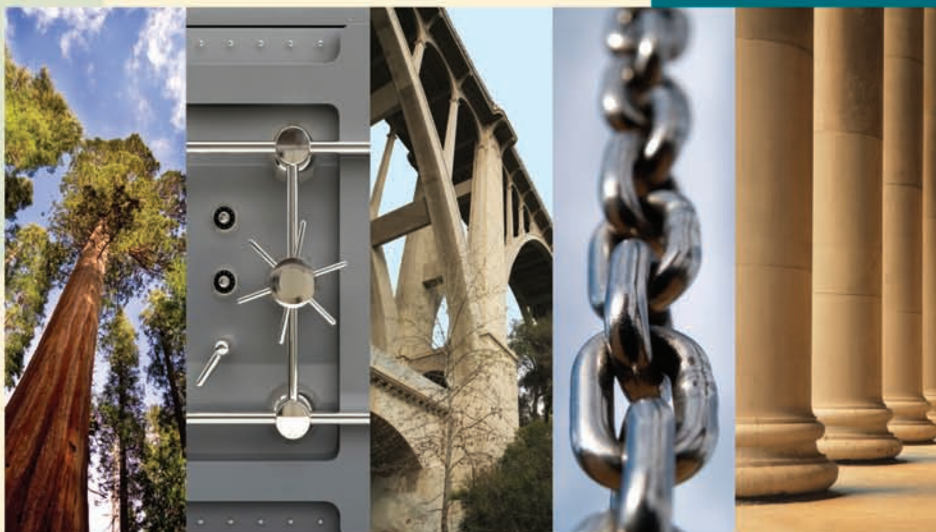

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OBITUARIES

# ANDREW LANGE

## 1957–2010

Andrew Lange, the Goldberger Professor of Physics at Caltech, passed away on January 22, 2010. He was 52.

Lange had been at Caltech since 1993. He graduated from Princeton University with his BA in 1980 and received his PhD from UC Berkeley in 1987. He first came to the Institute as a visiting associate in 1993–94, was appointed a full professor in 1994, and was named the Goldberger Professor in 2001. In 2006 he was named a senior research scientist at the Jet Propulsion Laboratory and in 2008 was appointed chair of the Division of Physics, Mathematics and Astronomy. He had recently resigned from his chairmanship of the division.

The principal focus of Lange's research was the cosmic microwave background, or CMB—the afterglow from the Big Bang that fills the entire universe. He developed a new generation of radio-frequency detectors that he employed as the leader of a string of experiments to study the CMB. He is perhaps best known for coleading the BOOMERanG (Balloon Observations Of Millimetric Extragalactic Radiation and Geophysics) experiment. BOOMERanG was the first experiment to map the CMB in fine enough detail to show that the universe is flat, meaning that space is neither closed, like the surface of a sphere, nor open, like a hyperbolic saddle. The data also measured the abundance of the dark matter known to hold galaxies together, and supported previous measurements that suggest that the universe's expansion is proceeding at an ever-increasing rate, implying either a violation of Einstein's general relativity or that the universe is filled with "dark energy," some exotic, unknown repulsive force. BOOMERanG also confirmed the predictions of the inflationary theory, which aims to explain the very earliest fraction of a nanosecond after the Big Bang.

Lange's subsequent work improved upon these measurements and attempted to detect gravitational waves by their effect on the CMB.

Lange was also one of the leaders of the recently launched Planck satellite, a collaboration between U.S. and European scientists designed to image the CMB with unprecedented precision.

Lange was a member of the American Academy of Arts and Sciences, the National Academy of Sciences, and the American Physical Society. Lange and Saul Perlmutter (from the Lawrence Berkeley National Laboratory) were jointly named the 2003 California Scientist of the Year for their seminal contributions to cosmology. Lange shared the 2006 Balzan Prize for Observational Astronomy and Astrophysics with Paolo de Bernardis (of the University of Rome), his BOOMERanG coleader. The two shared the 2009 Dan David Prize with Paul Richards, a coleader of the parallel MAXIMA experiment.

He is survived by three sons, ages 12, 14, and 20; his sister, Karen; his brother, Adam; and his parents, Joan and Alfred. A memorial service is being planned. E&S

# LEW ALLEN JR.

## 1925–2010

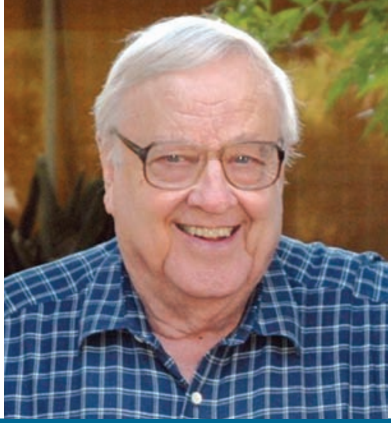
Former director of NASA's Jet Propulsion Laboratory Lew Allen Jr. passed away on January 4 at the age of 84, in Potomac Falls, Virginia. He led the laboratory from 1982 to 1990, during a period that included the launches of the Galileo mission to Jupiter, Magellan to Venus, and the Infrared Astronomical Satellite, as well as Voyager 2's Uranus and Neptune flybys.

Allen was born on December 30, 1925, in Miami. He studied at the United States Military Academy at West Point, New York, and had a distinguished career in the U.S. Army and the Air Force, where he remained until 1982, achieving the rank of four-star general and serving as chief of staff of the Air Force.

In 1954, while still an Air Force officer assigned to the Los Alamos National Laboratory in New Mexico, Allen completed his doctorate in nuclear physics. He specialized in the potentially damaging effects of high-altitude nuclear explosions on the ground and on spacecraft.

After leaving Los Alamos in 1961, Allen served in various scientific posts within the Office of the Secretary of Defense and the Office of the Secretary of the Air Force. He became director of the National Security Agency in 1973. He was also a member of the National Academy of Engineering and the Council on Foreign Relations.

A funeral service will be held at Arlington National Cemetery on March 22. A memorial service at JPL is being planned for the near future.
*— JP* E&S



# JAMES K. KNOWLES

1931–2009

James K. Knowles, Kenan Professor of Applied Mechanics, Emeritus, died November 1. He was 78.

Knowles made fundamental contributions to the theory of nonlinear elasticity and the mathematical theories of materials and structures. His work provided important insight into how various materials and structures behave, and enabled him and others to develop predictive theories.

Born in Cleveland, Ohio, on April 14, 1931, Knowles grew up in Phoenix, Arizona. He entered MIT in the fall of 1948, earning his bachelor's and doctoral degrees, both in mathematics, in 1952 and 1957, respectively. He then stayed at MIT for an additional year as an instructor in mathematics.

Knowles joined the faculty at Caltech in 1958 as assistant professor of applied mechanics; he was named associate professor in 1961, followed by full professor in 1965. He spent the remainder of his academic career at Caltech, becoming professor emeritus in 1997.

Considered a remarkable teacher and mentor, Knowles inspired and influenced generations of students and scholars through classes in mathematics and mechanics. A visionary thinker, he recruited and mentored a number of junior colleagues who took Caltech in new and fruitful research directions. He had a deep affection for Caltech and served in various administrative capacities.

"Jim was the greatest mentor I ever had. He held my hand when I first came to Caltech as an assistant professor. He also taught me how to teach," says Ares Rosakis, chair of the Division of Engineering and Applied Science, and Von Kármán Professor of Aeronautics and professor of mechanical engineering. "He would look for the spark in people's eyes and help them make their dreams a reality. As we at Caltech seek to create the best mentoring opportunities for our young faculty, we should be guided by Jim's example."

Knowles's research was primarily focused on mathematical problems in structural mechanics, and in particular on linear and nonlinear elasticity, which is the study of how bodies deform reversibly under stress. In 1960, he provided the first solution for a dynamical problem in finite elasticity, and in 1966, he published what would turn out to be a seminal paper concerning the foundations of Saint-Venant's principle in linear elasticity theory.

His later papers on the influence of nonlinearity on point singularities, such as those found at the tip of a crack, demonstrated how they could lead to new phenomena.

In 1979, Knowles published a paper concerning the dissipation of mechanical energy during quasistatic motions of elastic bodies. This led to his later work on the evolution of metastable states of equilibrium, which had applications in phase transformations.

Knowles's contributions are described in more than 100 journal publications. In 1998, he authored a textbook for grad students entitled *Linear Vector Spaces and Cartesian Tensors* (Oxford University Press).

In 1991, he was made an honorary member of the Caltech Alumni Association in recognition of his distinguished service. That same year, the *Journal of Elasticity* dedicated an issue to Knowles on the occasion of his 60th birthday for "seminal contributions made to the field of elasticity."

"He set an example of scholarship and fundamental thought, both broad and deep, that challenged students as well as researchers," says Roger Fosdick, editor in chief of the *Journal of Elasticity*. "He was highly inquisitive, deeply thoughtful, masterfully insightful and always seeking an explanation. He made indelible marks of value during his life both personally and professionally, and he will most certainly be missed."

Knowles's contributions were also recognized by the Society of Engineering Science with the Eringen Medal, and by the American Society of Mechanical Engineers with the Koiter Medal.

Knowles was a fellow of the American Academy of Mechanics, the American Society of Mechanical Engineers, and the American Association for the Advancement of Science, and was associate editor for the *Journal of Applied Mechanics*. From 1985 to 1986, he served as president of the American Academy of Mechanics.

Knowles was known outside the classroom for his paintings and baritone voice. He was a regular member of the Caltech Stock Company, an ensemble of musically inclined faculty, staff, students, and friends best described as Caltech's own version of the Capitol Steps.

The Division of Engineering and Applied Science has established the James K. Knowles Lecture and

*Engineering & Science* welcomes letters. Send correspondence to Douglas L. Smith, editor, *E&S* magazine, Caltech mail code 1-71, Pasadena, CA 91125, or e-mail dsmith@caltech.edu. We reserve the right to edit any letters selected for publication for length, content, and clarity.



Caltech Solid Mechanics Symposium, to be delivered annually by an internationally recognized scholar chosen by the faculty. The first lecture, by Rohan Abeyaratne of MIT, is scheduled for February 27 at 9 a.m. in Beckman Institute Auditorium. The lecture will be followed by a daylong program of talks by 12 current grad students and postdocs from the Division of Engineering and Applied Science. Open to the public, the Knowles lecture and symposium will commemorate his contributions to solid mechanics, his love for Caltech, and his encouragement of young researchers.

Knowles leaves behind a wife, Jacqueline, and sons John, Jeff, and James, and their families. — *JW* E&S

# F. BROCK FULLER

## 1927–2009

F. Brock Fuller, emeritus professor of mathematics, died on November 6 at the Rafael Convalescent Hospital in San Rafael, California, four years after being diagnosed with diffuse Lewy body disease. He was 82.

After receiving his bachelor's, master's, and PhD degrees from Princeton, Fuller came to Caltech in 1952 as a research fellow. He became an assistant professor of mathematics in 1955 and was appointed associate professor in 1959, and professor in 1966. In 1994, he became professor emeritus.

Fuller worked on the topology of how curves twist and coil, an endeavor prompted by the need for a quantifiable description of the supercoils being found in double-stranded DNA helices. A DNA supercoil forms when the famed double helix is itself twisted and coiled, the way the cord on the wall phone in your kitchen likes to do. A DNA molecule can be thousands of times longer than the cell whose blueprints it contains, so twisting it into compact supercoils allows it to fit inside the cell. Fuller developed a quantity called a writhing number, which is the number of times the double helix crosses over itself. The sum of the writhing number and another quantity called the twisting number, which Fuller defined as the number of times each DNA strand twists around the other, together measure the amount of supercoil in the DNA.

In the early 1980s, Fuller—who was also an audiophile—was involved in analyzing digital recording technologies as they began to reach prominence in the audio-entertainment industry. Working alongside Caltech colleagues such as Gary Lorden (BS '62) and James Boyk, Fuller examined music piped into Thomas Laboratory from Dabney Lounge, comparing various signals.

Fuller moved to San Rafael, in northern California, in 1996. He is survived by his wife, Alison Clark Fuller of San Rafael; his daughter, Lynn D. Fuller of San Francisco, her husband, William Bivins, and their four children, Samuel, Zachary, Elizabeth, and Claire Bivins; and his sister, Cornelia Fuller of Pasadena.
— *JW,MW* E&S

I take issue with a statement you make in your article: "Unfortunately, burning carbon dioxide back into hydrocarbons is very, very hard." It is only hard for human beings. Some species of algae find this task very easy. Melvin Calvin, a Nobel Prize winner from UC Berkeley, spent 25 years of his life studying plants that make hydrocarbons.

Calvin identified the genus *Botryococcus* as a remarkable source of hydrocarbons. He reported that the dry weight of this algae is 86 percent hydrocarbon! He identified the structures of some of the major components in the mixture. They fell into two groups: linear isoprene oligomers and cyclized steroids. Both of these products could be burned instead of coal to produce electricity and be fed to refineries in place of petroleum.

The work you wrote about requires two major investments to produce a feedstock that will replace coal or oil. The first is the solar power tower. The second is the Fischer-Tropsch unit. Neither is cheap compared to digging up coal or pumping up oil. The two investments cannot compete with skimming algae off the ocean surface and pressing out their hydrocarbons.

Too many entrepreneurs brag about how their invention will be competitive with petroleum in a few years. They are careful not to specify the price of the petroleum they are competing against. This is a real problem. The winning solution will be the one that requires the least new capital investment.

Frank Weigert [PhD '68]
Wilmington, DE

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