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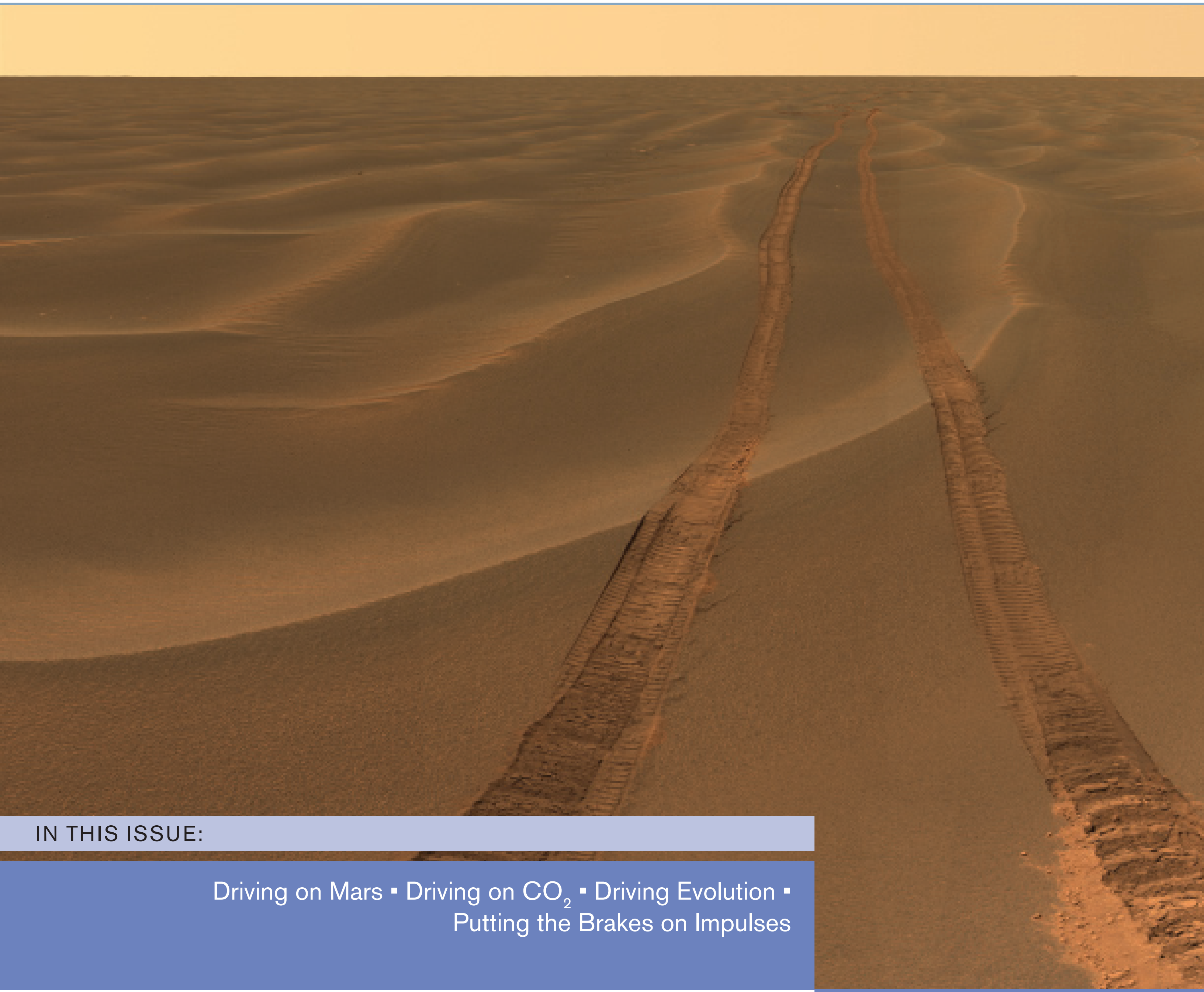
Engineering & Science



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Putting the Brakes on Impulses

VOLUME LXXII, NUMBER 2, FALL 2009

California Institute of Technology

ON THE COVER

The Mars rover Opportunity looks back at its tracks during its southward trek across sand dunes in Meridiani Planum. This image was taken in February, during the rover's current trip toward the 22-kilometer-wide Endeavour Crater. Already nearing its sixth year, the Mars Exploration Rovers have been one of the most successful planetary missions ever. Read the story on page 12.

LETTER FROM THE EDITOR

In the previous issue of *Engineering & Science*, I announced in this space that *E&S* and *Caltech News* would be suspending print publication at the end of the 2008–2009 fiscal year, with our content migrating to a vastly upgraded Web presence. This decision was part of an Institute-wide reorganization motivated by the desire to keep the financial challenges that face us all from affecting Caltech's core missions of education and research.

I heard from a broad spectrum of readers about this—from the class of 1940 to current undergraduates, from working moms to winners of the Nobel Prize and the National Medal of Science. Alumni, faculty, Caltech and JPL staff, and the broader community all weighed in. Some offered suggestions for the new website; most argued for the portability and durability of print. (A few of the comments appear on page 43.) Your opinions matter, and we will take your views into account as we plan the magazine's future.

Thanks to an anonymous benefactor, *Engineering & Science* will continue in print, at least through the 2009–2010 fiscal year. Meanwhile, the Office of Development and Institute Relations will be conducting a thorough analysis of all of Caltech's communications vehicles and their audiences. Rest assured that, regardless of the medium, the in-depth story of Caltech research will still be told, *E&S*-style.

On the electronic frontier, work on the new websites continues. Look for the launch sometime next year of a new supersite containing the best of *Caltech News*, *Caltech Today*, and *Engineering & Science* plus many new features. In the meantime, in the spirit of empiricism, I invite you to peruse a possible prototype of an interactive version of *E&S* online. Go to http://EandS.caltech.edu and click on the thumbnail of the cover. Let me know what you think!

Sincerely,

Douglas L. Smith
Editor
dsmith@caltech.edu
626-395-6730
Caltech Mail Code 1-71
Pasadena, CA 91125

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STAFF
Editor
Douglas L. Smith

Writer
Marcus Y. Woo

Contributing Writers
Allison Benter, Amy Lam, Lori Oliwenstein, Meg Rosenburg, Ann Wendland

Graphic Artist, Layout
Douglas Cummings

Copy Editors
Allison Benter, Barbara DiPalma, Sara Arnold, Michael Farquhar

Business Manager
Debbie Bradbury

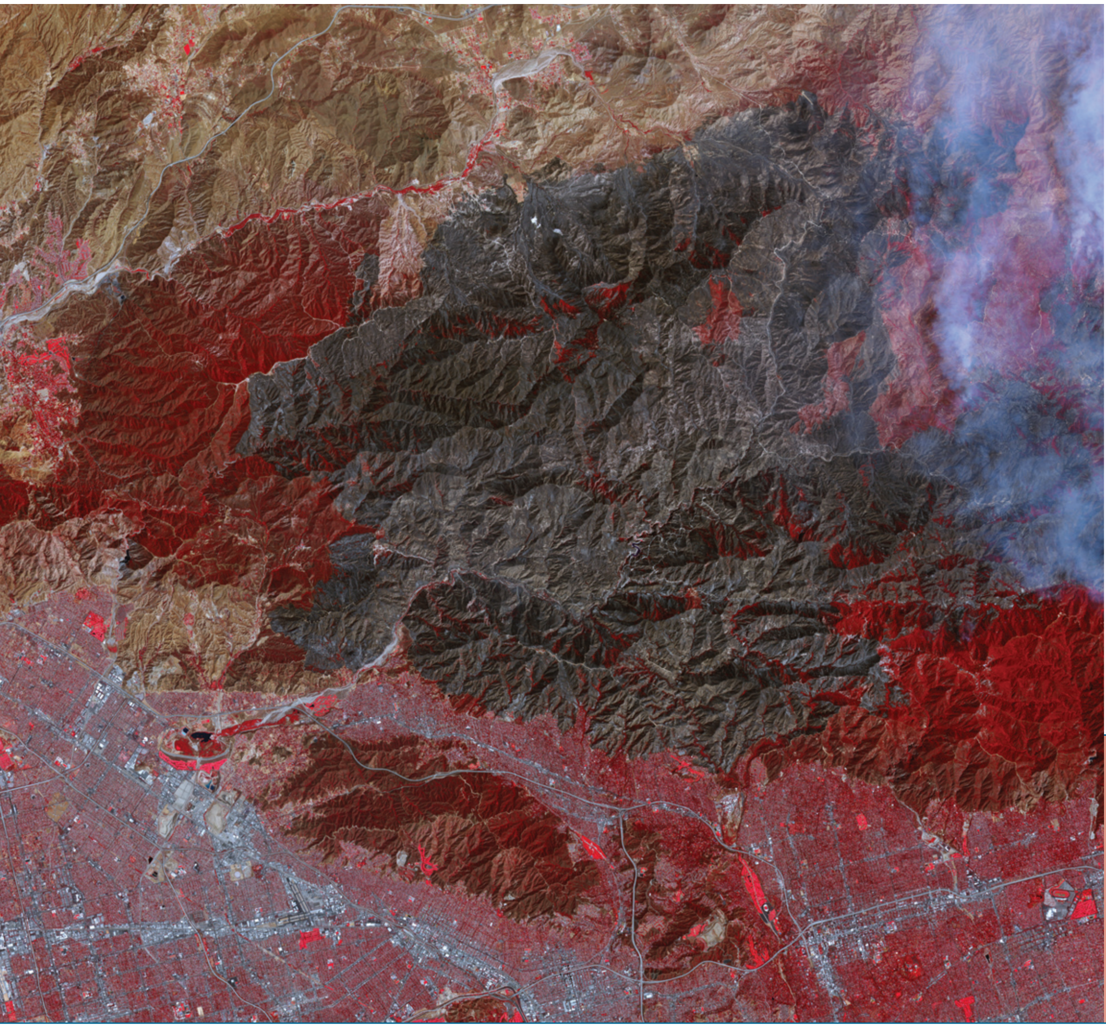
JPL UNDER FIRE

Fueled by triple-digit temperatures and single-digit humidity, the Station Fire has engulfed more than 160,000 acres of the Angeles National Forest in the San Gabriel Mountains north of Pasadena since being ignited by arson on the afternoon of August 26. The fire, which continued to smolder in some inaccessible canyons well into October, is the largest in the recorded history of Los Angeles County, and the 10th biggest wildfire in California since 1933. The fire killed two firefighters, injured 22 people, destroyed more than 200 buildings and homes, and cost about $90 million. Ash from the blaze fell as far away as Las Vegas, and the Los Angeles area was blanketed in a suffocating haze for weeks.

In addition to the hundreds of homes evacuated from Tujunga to Altadena, Caltech's Jet Propulsion Laboratory was closed during the last weekend of August when the inferno came within 0.2 kilometers of the Lab's northern edge. Only skeleton crews essential to keeping the Lab going and our far-flung fleet of spacecraft flying were allowed to report for work.

The flames also advanced up the slopes of Mount Wilson, overlooking Pasadena and home to crucial communication towers—including nearly all the local TV and many radio stations—that serve the Los Angeles region. Sharing the summit is the Mount Wilson Observatory, founded in 1904 by Caltech's George Ellery Hale. As the tool with which Edwin Hubble discovered the expanding universe, the 100-inch Hooker Telescope is arguably one of the most important scientific instruments in history. Over 100 firefighters from across California successfully defended the observatory and the antennas, dropping fire retardant from helicopters and setting backfires on the observatory grounds.

While the fire was burning within sight of JPL, JPL instruments on board NASA's Terra and Aqua



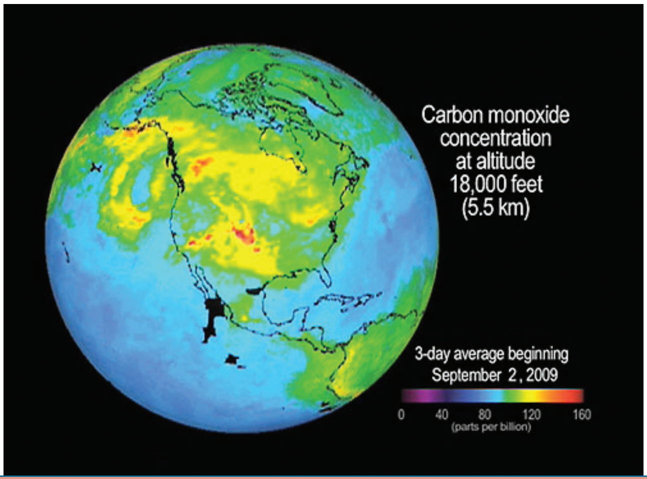
NASA/GSFC/METI/ERSDAC/JAROS, and the U.S./Japan ASTER Science Team

Left: The extent of the burned area (dark gray) as of September 6. This image was taken by Terra's Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), built by Japan's Ministry of Economy, Trade and Industry and run jointly with JPL.

Brent Buffington of the Cassini navigation team snapped this shot from the Devil's Gate Dam around 2:00 a.m. on August 29, as the fire was near its closest approach to JPL.

satellites were watching the fire from space. These satellites' polar orbits bring them back over the same piece of real estate every few days, allowing scientists to track all manner of global changes on a local or regional level.
—*MW* e&s

NASA/JPL



NASA/GSFC/LaRC/JPL, MISR Team

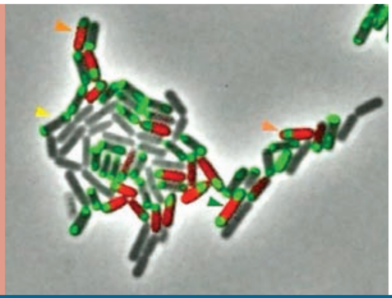
Above: The fire's carbon monoxide plume, seen by the Atmospheric Infrared Sounder (AIRS) on the Aqua satellite, eventually extended across the U.S. Right: Terra's Multi-angle Imaging SpectroRadiometer (MISR) captured this perspective view of white, puffy pyrocumulus clouds rising above the smoke plumes drifting across the Mojave Desert. This shot was taken at an off-vertical angle of 46 degrees and spans a width of almost 250 kilometers.

THE TROUBLE WITH GRADUALISM

What determines how many wings keep an insect aloft? Some have one pair, others two, but how is the correct number decided—was there once some poor intermediate bug blessed with 1.5? Now a team of researchers at Caltech and the Temple University School of Medicine has shown how evolution can be accomplished by "jumping" between forms, rather than going through a series of transitional states. "The intermediate states that occur along the way are not intermediate *forms*, but rather changes in the fraction of individuals that develop one way or the other," explains Michael Elowitz, the Caltech associate professor of biology and applied physics, Bren Scholar, and Howard Hughes Medical Institute investigator who led the research.

The key to this work lies in the fact that a single mutation can suddenly give a simple organism a lot of options, whereas an unmutated specimen always proceeds according to the same tightly scripted plan. "They don't only show a different morphology," says Avigdor Eldar, a postdoctoral scholar at Caltech and the first author of the group's recent *Nature* paper. "They show more variability in their behavior." The degree to which any particular outcome prevails among a population is called its penetrance. "Our work shows how

In this frame from a sporulation movie, the green arrow points to a bacterium (fluorescing red) that has successfully produced two spores (fluorescing green). The orange arrows show bacteria that have produced one spore each, and the yellow arrow points to a bacterium that tried to produce two spores without making a third copy of its DNA for itself.



partial penetrance can play a role in evolution by allowing a species to gradually evolve from producing 100 percent of one form to developing 100 percent of another, qualitatively different, form," says Elowitz.

Other mutations and nongenetic "noise"—fluctuations in the amounts of certain proteins that act as middlemen in various cellular processes—can influence the penetrance of a particular end state. In fact, this evolutionary pathway depends on noise to work at all. But only recently have scientists been able to analyze this variability, with the aid of such technological advances as time-lapse movies and fluorescent protein markers. In the past, researchers could only observe the average traits of a population of cells by growing colonies of bacteria, killing them at different time intervals, and studying the aftermath. That approach misses both the population dynamics and the fates of individual cells. A study like this one would simply not be possible—the entire phenomenon would be averaged over and lost.

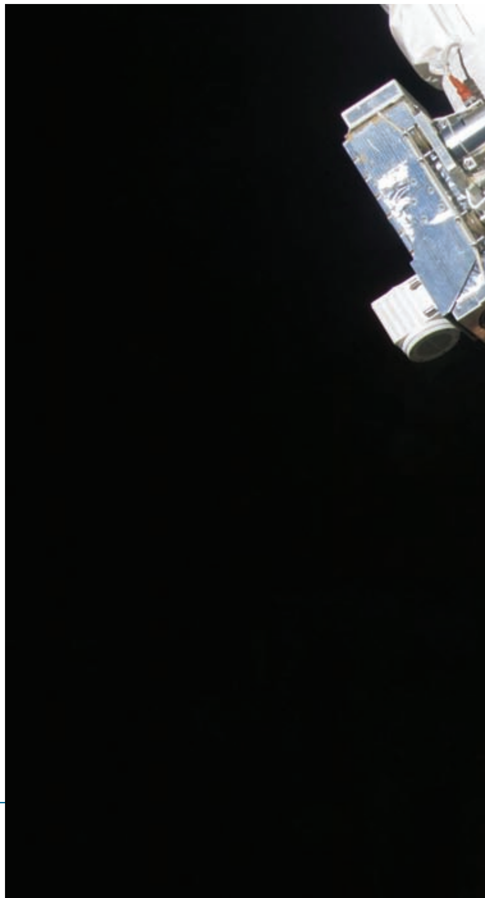
But these experiments put the individual front and center. The group studied the process by which a bacterium called *Bacillus subtilis* produces spores to preserve its genetic material during hard times. In the wild, *B. subtilis* bacteria create just one spore, but in the laboratory, other outcomes are possible. The researchers looked at a strain with a specific mutation that suppresses the signals passing between mother and spore, confusing the mother as to whether or not she has successfully sporulated. "Usually," explains Eldar, "these cells talk with each other, with the spore telling the mother, 'I'm here, and I'm doing OK.' In the wild-type cell, this chatter is loud; in the mutant, it's just a whisper, and the mother can't always hear."

When the mutants fall mute, any of four things could happen. First, the cell might proceed normally, copying its DNA once and producing one spore. The three alternatives involve variations in the number of spores produced and the number of DNA copies made. The cell might try to create two spores while making only one copy of its DNA, in which case one daughter gets the mother's chromosome and the other gets the copy, causing the mother to die before sporulation is complete. Or the mom might overdo it on the DNA copies but only make one spore, resulting in a harmless "extra" copy for herself. And finally, the cell could do both things right, making two copies and two healthy spores—other bacteria are known to do this, and it could offer *B. subtilis* an evolutionary advantage.

The team started by breeding bacteria with the whispering mutation. While all four possible fates were observed, the two-spore outcome was pretty rare. The researchers then added further mutations designed to encourage DNA replication, a move intended to boost the proportions of two of the fates—the twin spores, and the mother with extra DNA—at the expense of the others. As a result, the percentage of bacteria that produced two spores increased dramatically, from 1 to as high as 40 percent. "You can't switch from 1 to 1.1 spores," Eldar explains. "But it's easy to find a mutation that simply changes the frequency of the behavior. If 10 percent of the population makes 2 spores and the rest makes 1, that works. It solves the need for a quantum jump between 1 and 2 spores."

The paper was published online by *Nature* on July 5. The other authors are Caltech staffer Michelle Fontes and grad student Oliver Losón; Vasant Chary, Panagiotis Xenopoulos, and Patrick Piggot from the Temple University School of Medicine; and Jonathan Dworkin from the College of Physicians and Surgeons at Columbia University.

The Howard Hughes Medical Institute, the National Institutes of Health, the National Science Foundation, the International Human Frontier Science Organization, and the European Molecular Biology Organization supported the work. —*MR* e&s



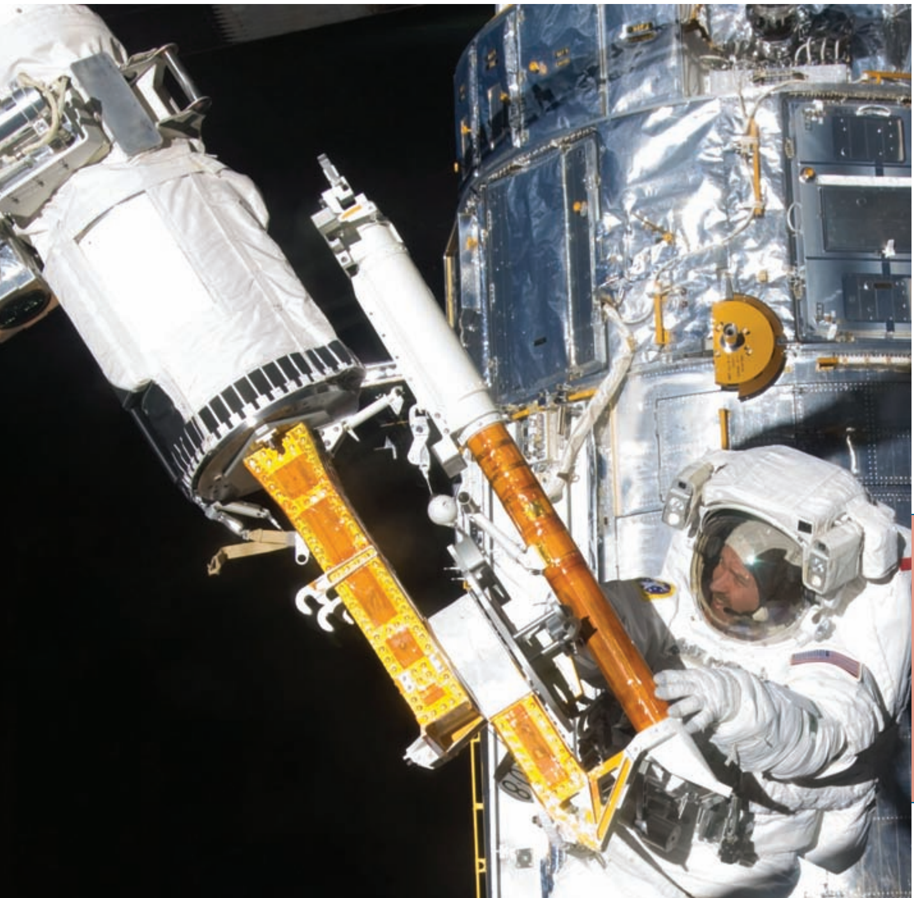
STAYING FIRM UNDER PRESSURE

Back in the day, before the meter was defined in terms of the speed of light, it was set as 1/10,000,000 of the distance between the equator and either pole along the meridian that passes through Paris. Rather than sending out surveyors whenever someone needed to know the exact length of a meter, the French Academy of Sciences created a meter-long metal bar known as the prototype. Made out of an unusually thermally stable but very expensive platinum-iridium alloy, the prototype was kept in a vault at the International Bureau of Weights and Measures in Sèvres, France, near Paris. Replicas of the prototype would be made and distributed as needed. The replicas were created using the same alloy, making them unaffordable to most people. Using cheaper materials was undesirable due to thermal expansion—until 1896, when Swiss scientist Charles Édouard Guillaume, head of the bureau, discovered an inexpensive iron-nickel alloy that would not expand when heated. Since then, several other "Invar" materials (so named because of their temperature-invariant properties) have been discovered. Though their internal mechanics remain controversial, modern Invar alloys find applications in many everyday items, such as toasters, computers, watches, and light bulbs.

Now Caltech grad student Michael Winterrose, Professor of Materials Science and Applied Physics Brent Fultz, and their colleagues have found a new way to induce Invar behavior in materials. By placing an iron-palladium alloy under high pressure, they were able to change it from an alloy that displayed no Invar behaviors to one that undoubtedly did.

Winterrose and Fultz were studying alloys composed of one part iron and three parts nickel, palladium, or platinum. Though nickel and iron atoms are nearly the same size, palladium and platinum are much larger. Winterrose and Fultz had planned to investigate the effects of high pressure on materials made of atoms of mismatched sizes, versus alloys of similarly sized atoms, hoping to discover interesting volume effects.

Winterrose and Fultz would place tiny samples of their alloys between two diamonds in what is called a diamond anvil cell. Tightening six screws forces the diamonds together, generating pressures of up to 33 gigapascals (GPa), or more than



Former Caltech Senior Research Fellow in Physics John Grunsfeld on the fifth and final spacewalk of the STS-125 shuttle mission to service the Hubble Space Telescope in May. Astronauts installed two new instruments—the Wide Field Camera 3 and the Cosmic Origins Spectrograph—and repaired two others, swapping out circuit boards that were never intended to be replaced.

300,000 times atmospheric pressure. With temperature kept constant, if pressure is increased, most materials contract at a relatively constant rate.

For the palladium-iron sample, however, that was not the case. At around 10 GPa, the Pd_3Fe sample began to compress more easily than before, and at around 15 GPa, the material became stiffer than it had been originally. This strange pressure-volume curve was baffling—that is, until Winterrose recalled that similar curves appear in a few other iron alloys. However, those curves were associated with Invar materials, which have unique magnetic properties that cancel out thermal expansion—properties that Pd_3Fe does not normally exhibit.

A computer simulation suggested that the high-pressure stiffening of the material might be due to a magnetic transition. "Perhaps the best early hint was found in the calculations of electron energies in Pd_3Fe. For high pressures, the spectrum of electron energies showed the fingerprints of an instability, where the magnetism was about to collapse, and a different set of electron levels would then become occupied," recalls Fultz.

Armed with their sample, Winterrose, Fultz, and company went to the Advanced Photon Source at the Argonne National Laboratory. There, they used a technique called nuclear forward scattering that allowed them to excite the magnetic states of their material, confirming that such a transition was indeed taking place—in fact, at the same pressures where the volume collapse occurred. As the electron configuration changed, the energy structure became closer to that of the traditional Invar material Fe_3Pd. "In this way," Winterrose says, "it's like alchemy. We've coaxed one material into behaving like another."

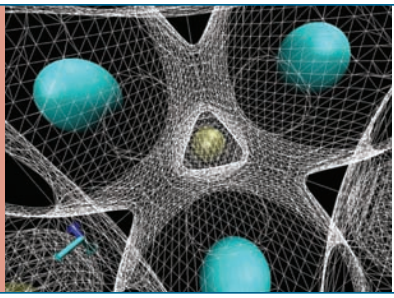
Finally convinced that they had an Invar material on their hands, Winterrose and Fultz performed one last test—they heated their troublesome alloy while it was being pressurized. And sure enough, they found that it did not expand at temperatures up to 250 degrees Celsius.

"Now that we've found an electronic structure change associated with Invar behavior, perhaps we will be able to find other means to cause similar changes and so create new Invar materials at lower pressures," Winterrose says. "This also demonstrates the possibility of manipulating the electronic properties of matter using simple mechanical force, and offers insight into the materials existing at high pressures that make up a large part of the matter in our solar system."

A paper describing their work was published in the June 12 issue of *Physical Review Letters*. In addition to Winterrose and Fultz, the coauthors are Matthew S. Lucas (MS '05, PhD '09), grad students Alan F. Yue, Lisa Mauger, and Jorge Muñoz (MS '09), and visiting scientist Itzhak Halevy, from Caltech; Jingzhu Hu, from the University of Chicago; and Michael Lerche, from the Carnegie Institution for Science.

The work was supported by the Carnegie–Department of Energy (DOE) Alliance Center, funded by the DOE through the Stewardship Sciences Academic Alliance of the National Nuclear Security Administration; by the DOE's Office of Science, Office of Basic Energy Sciences; by the National Science Foundation and its Consortium for Materials Properties Research in Earth Sciences (COMPRES); and by the W. M. Keck Foundation. —*AL* e&s

A rendering of electron density surfaces surrounding the iron (yellow) and palladium (blue) atomic cores in Pd_3Fe, based on calculations from first-principles quantum mechanical simulations. At a pressure of 12 GPa, the electron density begins to migrate toward the iron atoms, leading to Invar behavior.



THERE'S WATER ON THE MOON . . .

When the Apollo astronauts landed on the moon, they found its airless surface to be bone-dry. Now, 30 years later, a fleet of spacecraft have discovered traces of water there. But before you plan your trip to a lunar beach, bear in mind that the wet stuff exists as molecules embedded here and there in the regolith, the lunar equivalent of soil.

JPL's Moon Minerology Mapper (M^3) on the Indian spacecraft Chandrayaan-1 found traces of water and hydroxyl, a molecule consisting of one oxygen atom and one hydrogen atom, in the top two millimeters of the regolith. M^3 measured the sunlight reflected from the lunar surface and found that a wavelength of around three microns was being absorbed, the spectral signature of an O—H bond. The signal appeared all over, but was strongest near the poles.

Two other spacecraft confirmed the discovery, which was reported in the online edition of *Science* on September 24. Previously unpublished data from Cassini, which passed the moon in 1999 en route to Saturn, showed a similar signal. And comet hunter EPOXI, née Deep Impact, sealed the deal in a flyby in June with its high-resolution spectrometer.

Scientists aren't sure how much water there is, but models estimate that the abundance could be as much as 1,000 parts per million. In other words, wringing out one ton of the lunar surface would just fill your 32-ounce sipper bottle. —*MW* E&S

. . . AND MORE ICE ON MARS

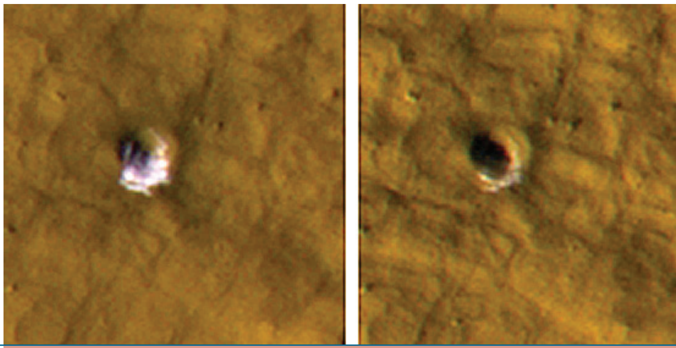
The poles aren't the only places on Mars with ice. JPL's Mars Reconnaissance Orbiter (MRO) found that several small meteorites had struck Mars in the last year, uncovering bright white water ice in the resulting craters. The fact that there was ice at all was surprising—the icy craters were in latitudes thought to be too low, and therefore too dry, for ice to exist.

The icy craters were between the latitudes of 45 and 55 degrees north—near where Viking 2 landed in 1976. In fact, had Viking dug just 10 centimeters deeper into the ground, it likely would've hit ice. Instead, the discovery had to wait another 33 years.

On August 10, 2008, MRO's Context Camera, which returns images of Mars in 30-kilometer-wide swaths, noticed a meteor crater that hadn't been there just 67 days before. Scientists then took a closer look with the High Resolution Imaging Science Experiment (HiRISE), and they saw brilliant white. The area was too small for MRO's onboard spectrometer to analyze, but the researchers found a larger, newly formed crater nearby and confirmed the suspicious material to indeed be water ice. In total, the team found ice in five small craters, which ranged in depth from a half-meter to 2.5 meters deep. After a few months, much of the whiteness disappeared as the ice sublimated and became mixed in with dust.

The 18 researchers from six institutions reported their findings in the September 25 issue of *Science*. —*MW* E&S

NASA/JPL-Caltech/University of Arizona



This brand-new, six-meter-diameter crater was shot by HiRISE on (left) October 18, 2008, and (right) January 14, 2009. The bright material in the left-hand image is water ice exposed at the crater's bottom, which is estimated to be 1.3 meters deep. In the right-hand image, the ice has sublimated away in the northern-hemisphere summer or has been obscured by fresh dust.

In this still from a video, fluorescent dye gets dragged along right behind the jellyfish before eventually trailing off in its wake.

PLANKTON STIRS THE OCEANS

The winds, the tides, and—say *what?*—the ocean's tiniest swimmers may have roughly equal effects on the large-scale mixing that distributes heat, nutrients, and gases throughout the world's oceans, according to a new Caltech study. Oceanographers had previously assumed that water's viscosity would damp out any turbulence created by weak-swimming plankton. But John Dabiri (MS '03, PhD '05), associate professor of aeronautics and bioengineering, and grad student Kakani Katija think that so-called Darwinian mixing, named for Charles Darwin—no, not that Darwin; his grandson—might be able to transport huge volumes of water in very small batches.

"Darwin's grandson discovered a mechanism for mixing, similar in principle to the idea of drafting in aerodynamics, whereby an individual organism literally drags the surrounding water with it as it goes," Dabiri explains. Every day, billions of tiny krill and copepods migrate hundreds of meters from the depths of the ocean toward the surface. Darwin's mechanism suggests that they might drag some of the colder, heavier bottom water up with them toward the warmer, lighter water at the top. This would create instability, and eventually the water would flip, mixing itself as it went.

When Dabiri and Katija modeled this mathematically, they found that at very small scales, the water's viscosity actually *enhanced* Darwin's mechanism, magnifying the effect. "It's like a human swimming through honey," Dabiri explains. "What happens is that even more fluid ends up being carried up with a copepod, relatively speaking, than would be carried up by a whale."

Katija and collaborators Monty Graham (from the Dauphin Island Sea Laboratory), Jack Costello (from Providence College), and Mike Dawson (from the University of California, Merced) then traveled to the South Pacific island of Palau to study this effect among jellyfish, which are the focus of much of Dabiri's work and much easier to see than krill. When fluorescent dye was injected into the water in front of the jellyfish, the dye traveled right along with them, often for long distances.

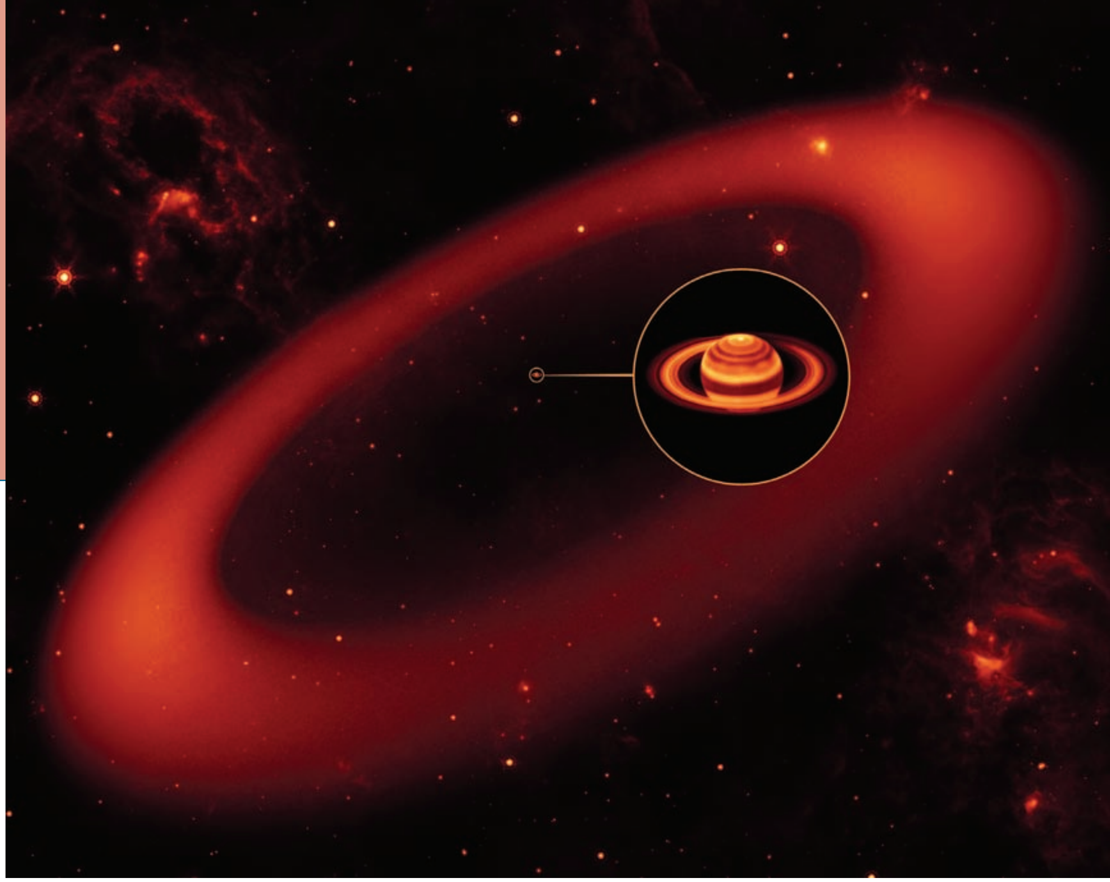
Dabiri and Katija calculated the impact of this so-called biogenic ocean mixing for a broad range of species. Says Dabiri, "There are enough of these small animals in the ocean that, on the whole, the global power input from this process is as much as a trillion watts of energy—comparable to that of wind forcing and tidal forcing."

And then there's a downbound process that they have yet to analyze, says Dabiri. Fecal pellets and marine "snow" made up of falling organic debris probably pull surface water toward the deeps. "This may have an impact on carbon sequestration on the ocean floor," says Dabiri. "It's something we need to look at in the future." Both effects will need to be incorporated into the computer models of global ocean circulation used to study climate change.

A paper on the work, written by Katija and Dabiri, appeared in the July 30 issue of *Nature*. The work was supported by grants from the National Science Foundation, the Office of Naval Research, the Department of Defense, and the Charles Lee Powell Foundation. —*LO* E&S

Listen to a podcast of John Dabiri talking about his work with jellyfish.

The Spizter Space Telescope has discovered a gigantic ring, visible in the infrared, around Saturn. If the ring, shown here in an artist's rendition, were visible on Earth, it would be twice the width of the full moon. The new ring is tilted 27 degrees from the main ring plane and follows the orbit of Saturn's retrograde moon Phoebe, which is the presumed source of the ring's material. The discovery team was led by Anne Verbiscer at the University of Virginia, Charlottesville.



Main image: NASA/JPL-Caltech/R.Hurt (SSC); Inset image: NASA/W.M.Keck Observatory/JPL-G. Orton

ULYSSES ENDS ITS ODYSSEY

After more than 18 years and almost three complete polar orbits around the sun, JPL's controllers of the Ulysses spacecraft have called it a mission. The joint NASA/ESA spacecraft was shut down on June 30 as it began to slowly succumb to the cold of deep space. (Ulysses' six-year orbit takes it out to Jupiter and back.) The doughty probe had exceeded its designed lifetime by nearly fourfold and covered almost two complete 11-year cycles of solar activity, providing grist for more than 1,000 scientific papers and two books so far.

Ulysses was the first mission to survey the north and south polar regions of the heliosphere, the "bubble" created by the solar wind. Besides monitoring the solar wind and the local magnetic field, the spacecraft measured radio, X-ray, gamma-ray, and particle emissions from the sun, Jupiter, deep space, and even a couple of passing comets, flying through their tails. —*DS* e&s

CCAT TAKES THE TORCH

A rough road switchbacks up the flanks of Cerro Chajnantor in Chile's Atacama Desert and levels out on a small plateau 80 feet below the summit. If you stood on that plateau, 18,500 feet above sea level in the driest desert on Earth, you might first notice the absence of life—no plants rustle in the wind, no lizards dart among the rocks. Below, golden desert stretches between the coastal mountains and the Andes, isolated by their rain shadows from both ocean storms and humid gusts from the Amazon Basin. The great plain has no correspondingly great river, the peaks no glaciers, and the air almost no moisture. If you set a glass on the dirt and condensed all the water vapor in the air above the glass into it, the collected water would stand at less than a millimeter. With its thin, parched atmosphere, this is the premier location for CCAT, a planned submillimeter-wavelength observatory that goes by the working title of Cerro Chajnantor Atacama Telescope. According to CCAT deputy project manager Simon Radford, our view of the submillimeter sky, which is limited by atmospheric water vapor, is better here than anywhere except Antarctica and space, where construction and upgrades would cost a bit more.

When the veil of water vapor is lifted, the universe is as bright at submillimeter wavelengths as it is in visible and ultraviolet light combined. Clouds of gas and dust that appear dark to our eyes and to optical telescopes shine in submillimeter light, revealing massive stellar nurseries and hidden galaxies.

Nobel laureate in physics Robert Wilson, PhD '62, who chaired the observatory's technical review committee, predicts that CCAT "will revolutionize astronomy" in the submillime-

PICTURE CREDITS
4 — Avigdor Eldar; 4-5 — NASA; 6 — Michael Winterrose; 8 — Kakani Katija and John Dabiri

ter and far-infrared band and "enable significant progress in unraveling the cosmic origins of stars, planets, and galaxies." He emphasizes, "CCAT is very timely and cannot wait."

CCAT will succeed the legendary Caltech Submillimeter Observatory on Mauna Kea, which captured its first data in 1987. (See *E&S* Summer 1988.) When CCAT's eye opens in 2016, the CSO's eye will close. "The timing of this works very nicely," says Tom Phillips, CSO's director and the Altair Professor of Physics. "The international community of astronomers that relies on the CSO will have a seamless transition as CCAT comes online." After a good solid party in the CSO's honor, the telescope's site will be returned to nature. Though the site may appear as it once did, the universe never will.

The CSO was the brainchild of Robert Leighton (BS '41, MS '44, PhD '47), a physicist fascinated with underexplored wavelengths who taught at Caltech until his retirement in 1985 and often spent evenings building balsa-wood telescope models in his garage. Equipped with a 10.4-meter Leighton Dish and a state-of-the-art single-pixel receiver invented by Phillips, the CSO helped astronomers gain insight into the chemistry of space, the birth of nearby galaxies and stars, the composition of comets and planets, and the origins of terrestrial water. Designed for upgradability, the CSO also enabled tests of new detectors.

CCAT will see a broader wavelength range—from 200 micrometers to 2.2 millimeters—using the latest detectors. While the CSO started off with a single-pixel receiver, CCAT will sport two 50-kilopixel cameras based on Microwave Kinetic Inductance Detectors, or MKIDs. Invented by Jonas Zmuidzinas (BS '81), professor of physics and director of JPL's microdevices laboratory, along with JPL Senior Research Scientist Henry "Rick" LeDuc, MKIDs are superconducting photon detectors that are cheaper to fabricate and easier to assemble into large arrays than transition edge sensors, the competing technology. MKID arrays are also considered more likely to be scalable into megapixel cameras, for which CCAT's designers have thoughtfully left room. But MKIDs are relatively new. Zmuidzinas began working on them in 2000 with seed funding from Trustee Alex Lidow, BS '75, and the first prototype camera was installed on the CSO in 2007.

CCAT's dish, 2.5 times bigger and nearly twice as smooth as the CSO's, will gather more light and focus more sharply. David Woody, a key contributor to many Caltech telescope projects, is honing the design of the primary mirror and its support, in which some 1,800 reflector tiles premounted in groups on 200 "rafts" are secured to a carbon-fiber truss. A network of sensors and actuators will keep the surface smooth to within ten micrometers—between the width of a red blood cell and a white blood cell. "CCAT is a really tough technical challenge," says lead telescope designer Steve Padin, whose work with Woody is supported by a five-year gift from John B. and Nelly Kilroy.

Astronomers will use CCAT to test the prevailing wisdom about the evolution of galaxies, stars, and black holes. Here's the gist of the story. After the Big Bang, the universe—most of which is dark matter—varied slightly in density. Over billions of years, gravity emptied material from less dense areas into denser ones, which, in turn, merged into larger structures. As the dense regions merged, galaxies that had coalesced inside of them also gravitated toward each other, often colliding and merging. These smash-ups roiled the gas clouds within the galaxies, triggering bursts of star formation and causing much of the gas to sink toward the merged galaxies' cores, fueling the growth of supermasssive black holes.

Everything we can see fits this story, but the problem is that, at most wavelengths, the picture dims at the height of the action. In the universe's first few billion years, when all those

This false-color composite image of the Antennae galaxies uses infrared data from the Spitzer Space Telescope and visible data from the Kitt Peak National Observatory to show what we can expect from CCAT. The image sharpness is comparable, with the red dot in the lower left corner representing CCAT's 3.5-arc-second resolving power at 350 micrometers. The red box outlines CCAT's five-arc-minute-by-five-arc-minute field of view with the proposed ATACamera. By contrast, the red dot in the lower right corner shows ALMA's entire seven-arc-second field of view at 350 micrometers.

galactic collisions and mergers were making new stars hand over fist, those stars were born enshrouded by gas and dust, making them invisible. But the copious ultraviolet light from the new stars heated that dust, which reradiated the heat at longer wavelengths that penetrate the dust and are visible to CCAT, enabling astronomers to tell what happened behind the curtain.

Recent submillimeter observations have turned up hundreds of distant galaxies that give off most of their light in the submillimeter and far-infrared bands. These are the ancient, colliding galaxies that astronomers want to see. Big, fast, and sensitive, CCAT will find hundreds of thousands of such objects. CCAT will survey the submillimeter sky from the earliest era of galaxy formation forward, measuring luminosity, redshift, and color.

Astronomers will sift through this wealth of newly discovered galaxies for those with the most potential to refine the story, and will follow up with closer observations at narrowly focused instruments like the Thirty-Meter Telescope and the Atacama Large Millimeter / Submillimeter Array (ALMA), an interferometer under construction on a plateau 2,000 feet below CCAT.

At the other end of the cosmological scale, CCAT will turn its dust-vision on our own sun's remnant disk—the Kuiper Belt beyond Neptune—to catalog and analyze hundreds of objects dating back to the birth of our solar system. This and CCAT studies of other stellar disks, from protoplanetary systems to old debris, will offer new insights into how planetary systems form.

As planning for CCAT advances, the community of interested astronomers swells. CCAT, initially the Cornell Caltech Atacama Telescope, got its new working title in recognition of the consortia of British, German, and Canadian astronomers, plus American partners, including the University of Colorado and Associated Universities Inc., that have signed on.

"The worldwide community is excited about CCAT, and there is no shortage of potential partners. It is wonderful for Caltech and JPL to be in the position of playing a leading role in the development of this unique and powerful new telescope," says Andrew Lange, Goldberger Professor of Physics, who has made CCAT the Division of Physics, Mathematics and Astronomy's number-one priority since becoming division chair one year ago. —*AW* e&s

Spitzer: NASA/JPL-Caltech/Z.Wang (Harvard-Smithsonian CfA); Kitt Peak: Mary Jo Rushing and Jim Lawler/Adam Block/NOAO/AURA/NSF

Roving on Mars

Having spent almost six years on the red planet, the Mars Exploration Rovers are proving to be one of the most successful missions of all time, revealing a wet and complex world.

On May 6, 2009, Spirit got stuck. The Mars rover, about the size of a go-kart, was traveling south on the red planet when it found itself hubcap-deep in loose, flourlike sand. To make matters worse, the rover's right front wheel had locked up three years earlier, leaving it with only five working ones. Fearful of its digging in deeper with every turn of the wheels, Spirit's controllers at JPL called a halt until they could find a way to get it out. Since then, the engineers have been testing maneuvers here on Earth in a big sandbox with two rovers—an exact replica and a lighter one that's closer to what Spirit weighs on Mars. The team is still at it as of this writing, and so far this Spirit is anything but free.

Such setbacks aren't new, however. Less than three weeks after Spirit landed on January 4, 2004, it fell silent. Engineers scrambled to solve the problem, hoping there wouldn't be a repeat of the previous two American missions to Mars. On December 3, 1999, the Mars Polar Lander had been lost, apparently due to a software error that shut off its descent engine too soon. Accompanying the lander was the Mars Climate Orbiter, which was incinerated when a mix-up between metric and imperial units caused it to enter the Martian atmosphere too low. Mars is an unforgiving destination—in fact, more than a third of all spacecraft sent there have never made it. The memory of past failures was still fresh and, with Spirit, the future of the entire Mars program might well have been hanging in the balance. Meanwhile, Spirit's twin was

The Mars Reconnaissance Orbiter snapped this shot of Victoria Crater on October 3, 2006. The ripples at the bottom of the 750-meter-wide crater are sand dunes, created by wind-blown dust. If you squint, you can see the Opportunity rover at the crater's edge on the left, just above the widest lobe.

An artist's rendition of the lander enclosed in airbags as it bounces along the Martian surface. After it stops rolling, the airbags deflate and the lander unfolds to reveal the rover. For an animation of the trip to Mars, click here (RealVideo).

By Marcus Y. Woo

scheduled to land on the other side of the planet. With Spirit's life in doubt, everything now depended on the rover named Opportunity.

Fortunately, Opportunity landed without a hitch, and the team soon diagnosed Spirit's problem as a software glitch. By February, Spirit was back on track. The two machines, together known as the Mars Exploration Rovers (MERs), then began one of the most successful planetary missions ever. Designed to last only 90 Martian days, or sols, the MERs have now been roving for more than 2,000 sols—nearly six Earth years. These proxy geologists have poked and drilled their way into history, having explored an unprecedented amount of real estate on an alien planet. They have revealed conclusively a watery world with shallow lakes and seas, and with water underground, suggesting that at one time Mars could have been suitable for life.

Spirit and Opportunity wouldn't have been possible had it not been for their predecessor, the 1997 Pathfinder mission (see *E&S* 1997, No. 3)—NASA's first return to Mars since the Viking landers in the 1970s. The Pathfinder lander, which carried most of the instruments, brought along the original Mars rover, a lawn-mower-sized vehicle named Sojourner. This six-wheeled robot spent nearly three months exploring the Martian surface, taking thousands of pictures and analyzing the soil and rocks. Because the rover depended on Pathfinder to relay information back to Earth, Sojourner couldn't venture far and was restricted to covering 250 square meters—an area less than the size of a tennis court. Still, it was proof of principle that you could land a mobile robot on another planet, paving the way for future, more sophisticated vehicles.

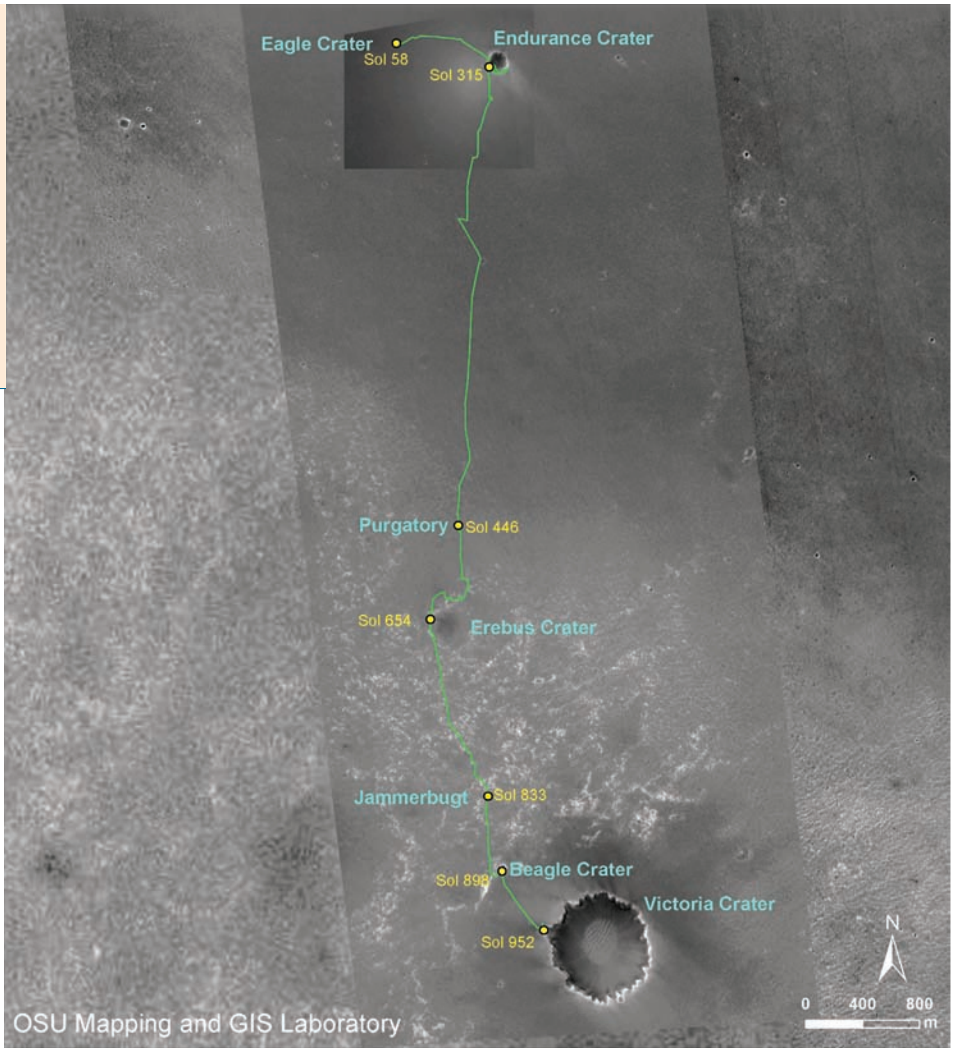
And Spirit and Opportunity are sophisticated indeed. Although they share the same basic six-wheeled design, if Sojourner were a push mower, the MERs would be John Deere yard tractors. They can talk to Earth directly via their own antennas or through orbiting spacecraft and have solar panels that generate about 140 watts of power; Sojourner could only produce a maximum of 16 watts. Instead of venturing just tens of meters from their landing sites, the rovers have together already traveled tens of *kilo*meters—far beyond what their designers were hoping. Sojourner's simple instruments—including three cameras and a spectrometer—were attached to its body. To identify minerals with its spectrometer, it had to drive right up to the rock. In contrast, each MER has *two* spectrometers at the end of a robotic arm that, with a shoulder, elbow, and wrist, has the same dimensions and maneuverability as a human one. Also attached at the end are a microscopic imager and a rock abrasion tool that drills into rock to expose the unweathered interior for analysis—the robot geologist's loupe and rock hammer, respectively.

Finally, each rover's high-resolution panoramic stereo camera, perched above the ground at a human's eye level, has perhaps been most responsible for capturing the public's imagination. Not only has it taken thousands of stunning images, bringing the Martian landscape to the living room, but this set of eyes has given the rovers an identifiable and humanized familiarity. The vehicles bear a remarkable resemblance to robots in pop culture, such as Number Five in the film *Short Circuit* and, most recently, the title character of *WALL-E*. (In fact, Pixar animators had used the rovers for inspiration when developing the film.) The anthropomorphizing of the rovers is made even easier by the fact that while space is an incomprehensibly large place, Spirit and Opportunity operate at the human scale. "What the rovers see isn't much different from what you would see wearing a space suit standing on the surface of the planet," says Richard Zurek, the chief scientist for the Mars Program Office at JPL and the project scientist for the Mars Reconnaissance Orbiter. It's this scale, Zurek says, that has helped make this one of the most publicly accessible missions.

As Steven Squyres of

The rover's eyes—a stereo panoramic camera that stands at roughly eye-level above the ground. The "eyes" are spaced 30 centimeters apart, providing full-color, 3-D panoramas of the Martian landscape.

A map of Opportunity's path through its first 952 sols. After spending two years exploring the outer rim of Victoria, Opportunity headed south toward Endeavour Crater 17 kilometers away. Now, the rover is about three kilometers south of Victoria.



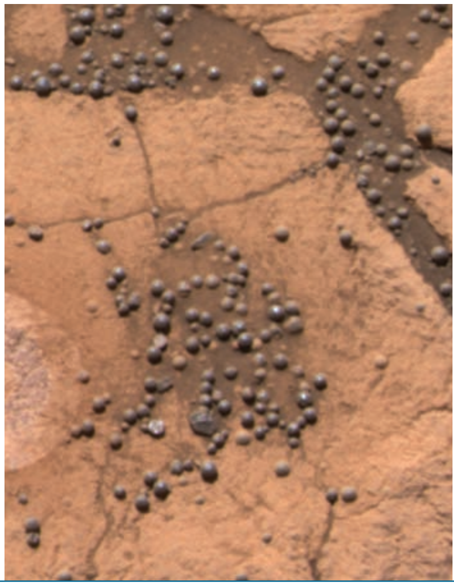
Cornell—MER's principal investigator—told Caltech alumni during last May's Seminar Day, it has been the adventure of a lifetime. "The goal of our mission," Squyres said to the crowd at Beckman Auditorium, "is to go to two places on Mars and try to read the story in the rocks and to learn what the conditions were like in the early days of Martian history. Was it warm? Was it wet? Would the conditions there be suitable for life?"

The two rovers were sent to two different sites on opposite sides of the planet. Spirit went to Gusev Crater (14.6° S, 175.3° E), which was chosen based on physical features—a dry river bed flows into it, suggesting the 150-kilometer-wide crater was once a lake. Opportunity's landing site on Meridiani Planum, near the equator (2.0° S, 6.0° W), was chosen based on surface chemistry. The Mars Global Surveyor, an orbiter launched in 1996, had observed patches of hematite, a type of iron oxide that often requires water to form, on Meridiani—the only place on Mars where large deposits of it were found.

Each spacecraft carrying a rover arrived at Mars careening at 5,400 meters per second—6,000 times the cruising speed of a 747. The atmosphere then slowed down the rover, packed in its aeroshell, to 430 meters per second—about seven times as fast as a Cessna—as the heat shield reached a scalding 1,400 degrees Celsius. Parachutes slowed it further, but because of the thin atmosphere, chutes weren't enough. Airbags covering the lander inflated and retro-rockets briefly fired. Looking a little like a big popcorn kernel, the lander was cut loose from the chutes at about 15 meters above the surface. After the lander finished bouncing around, the airbags deflated, and like mechanical origami, the lander's petals opened and the rover unfolded.

WHAT AN OPPORTUNITY

Opportunity settled into a 20-meter-wide crater—a 90-million-kilometer hole in one. As Squyres remarked, "Tiger Woods on his best day could not have pulled off this landing." Before the rover touched down, Squyres was worried that the surface of Meridiani would be too smooth, lacking enough



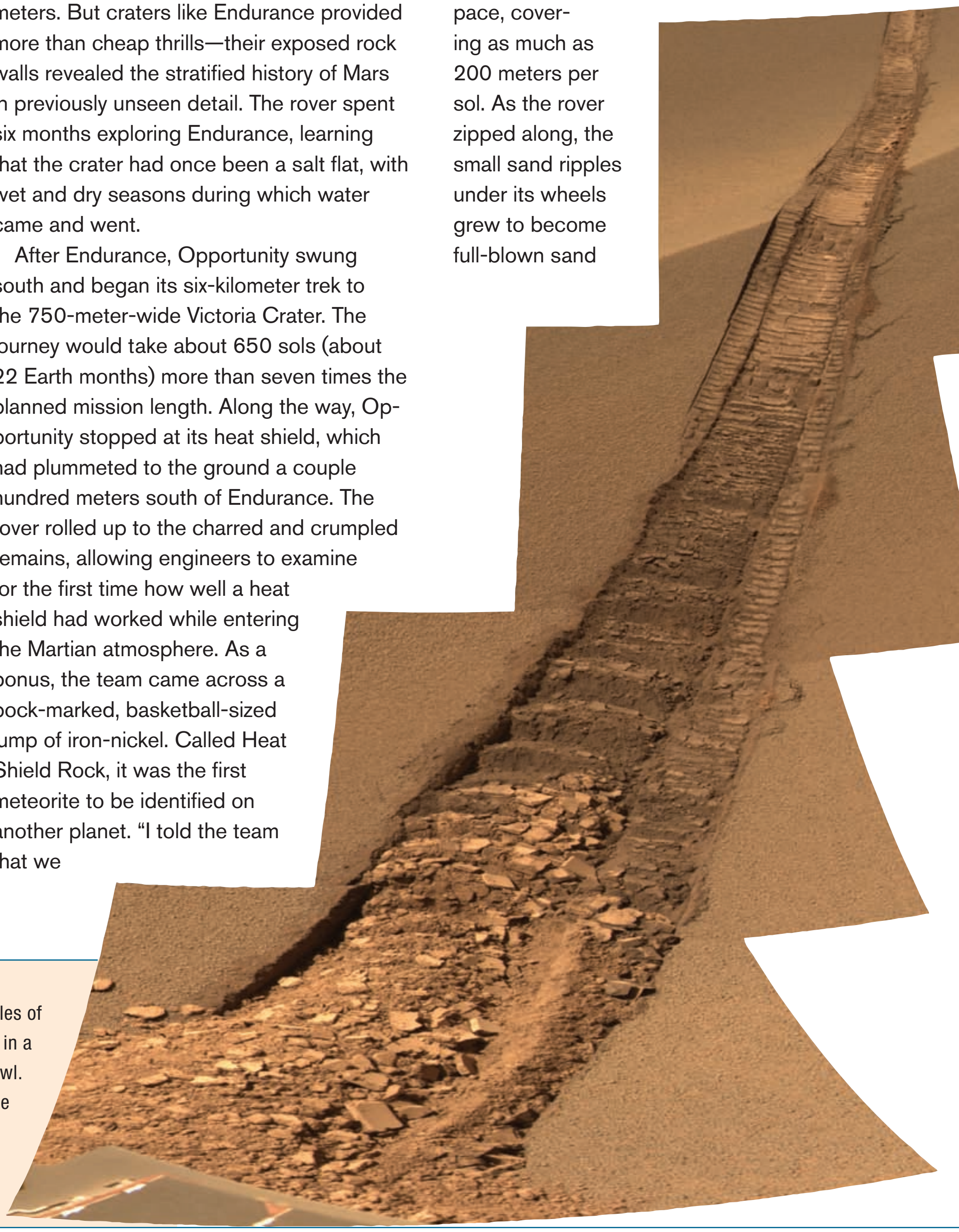
geological variation and rock to study. When Opportunity opened its eyes for the first time, however, it saw exposed bedrock, ripe for digging and analyzing. The team couldn't tell how high the outcrop was, and for all they knew it could've been quite tall, so they dubbed it the Great Wall. But after surveying it with the stereo camera and doing some math, they found out it was just 10 to 20 centimeters tall—barely ankle-high. Still, the entire landing site was full of exposed rock—crucial because it's relatively young and accessible.

Then, as Opportunity looked around, it made what is likely the mission's signature discovery. It saw small pebblelike objects scattered across the surface, and when it went over to take a closer look, it identified the five-millimeter spheres—dubbed blueberries—as hematite. The blueberries hadn't rolled in from somewhere else, but were embedded in the rock. They proved to be geological features called concretions, which require water to form. When water saturates porous sedimentary rock, minerals precipitate out and fill the voids inside the rock. Over time, the precipitates accumulate, layer by layer like an oyster's pearls, eventually forming the blueberries. Wind then erodes the surrounding rock to expose the hematite. The rock and soil surrounding the blueberries were rich in sulfates, another chemical signature of water. The researchers also saw petrified ripples in the sand, possibly created by slow-moving waves on an ancient shoreline.

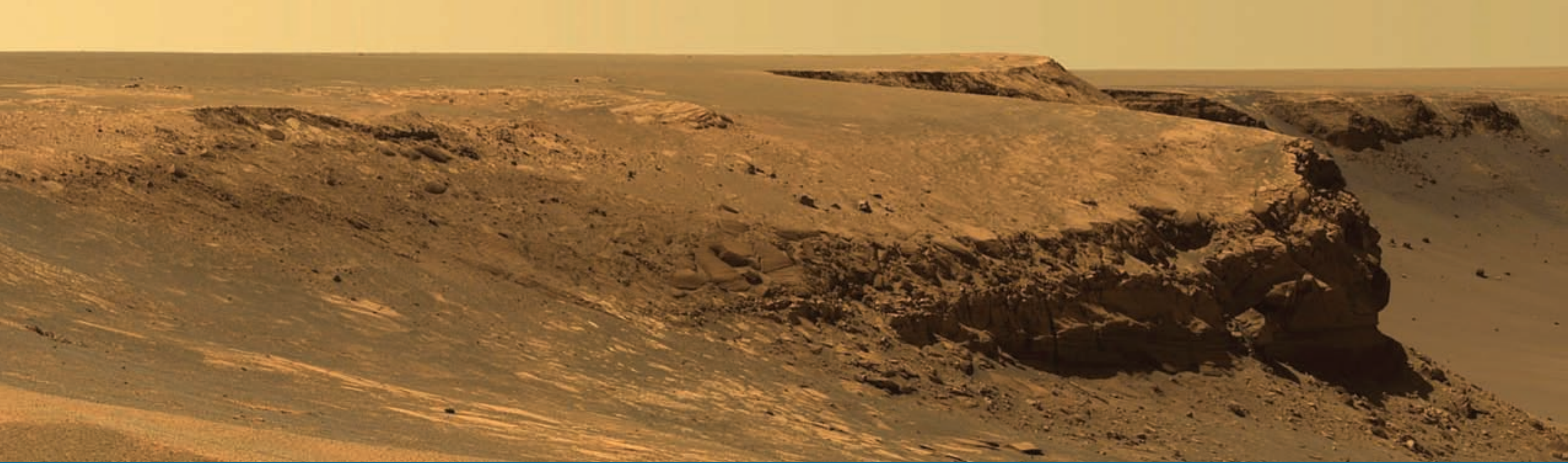
Opportunity explored this crater, called Eagle, for two months before starting the 800-meter trip eastward to Endurance Crater, which, with a diameter of 130 meters, was the size of a small stadium. Once there, Opportunity inched its way down the western ridge, an 18-degree slope, for about 17 meters. But craters like Endurance provided more than cheap thrills—their exposed rock walls revealed the stratified history of Mars in previously unseen detail. The rover spent six months exploring Endurance, learning that the crater had once been a salt flat, with wet and dry seasons during which water came and went.

After Endurance, Opportunity swung south and began its six-kilometer trek to the 750-meter-wide Victoria Crater. The journey would take about 650 sols (about 22 Earth months) more than seven times the planned mission length. Along the way, Opportunity stopped at its heat shield, which had plummeted to the ground a couple hundred meters south of Endurance. The rover rolled up to the charred and crumpled remains, allowing engineers to examine for the first time how well a heat shield had worked while entering the Martian atmosphere. As a bonus, the team came across a pock-marked, basketball-sized lump of iron-nickel. Called Heat Shield Rock, it was the first meteorite to be identified on another planet. "I told the team that we shouldn't stay here," Squyres said. "This is obviously a place where big metal objects fall from the sky."

There were a few brief stops along the way at smaller craters, but Opportunity maintained a brisk pace, covering as much as 200 meters per sol. As the rover zipped along, the small sand ripples under its wheels grew to become full-blown sand



Left: Soon after landing, Opportunity discovered pebbles of hematite embedded in sedimentary rock, like blueberries in a muffin. The team called this site the berry bowl.
Top: Smash! Opportunity explores its fallen heat shield. The main part is on the left; the impact site is on the right.
Right: Opportunity's tracks during its effort to free itself from Purgatory Dune.



dunes, and halfway between Endurance and Victoria, Opportunity got stuck. The wheels racked up 50 more meters on the odometer before anyone realized the rover hadn't actually gone anywhere. (The team aptly named this unplanned stop Purgatory Dune.) To figure out how to get the rover out, they had to recreate its situation, so they fanned out to hardware stores across the Los Angeles area to buy the ingredients for mock Martian soil: sand, clay, and diatomaceous earth—a material made of ground-up fossilized algae that is used in swimming-pool filters. After six weeks with the rover in Purgatory, according to Squyres, the team discovered that the best way to spring the vehicle free was "to put it in reverse and gun it." With its renewed freedom, Opportunity continued to Victoria Crater, where it would spend the next 682 sols.

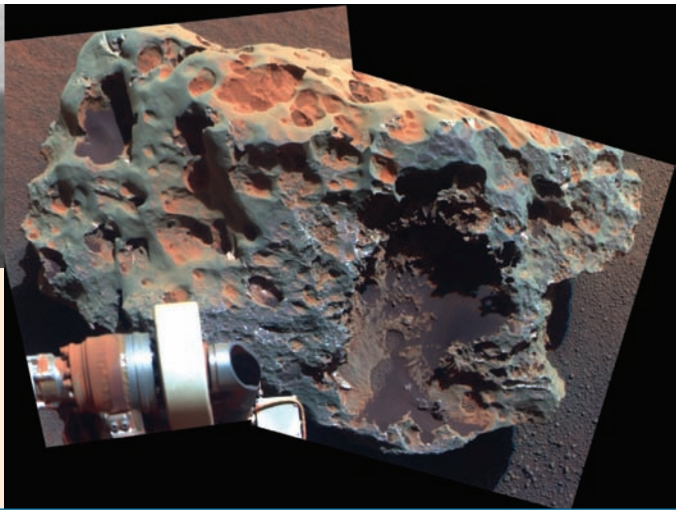
Victoria is 75 meters deep, and although Opportunity didn't go all the way to the bottom, where the rover would have become mired in a dune field, this expedition was the deepest yet. The rover spent nearly two years exploring the edge and outer regions of the crater, venturing in when the slope was shallow and safe, finding more evidence of water and of wind erosion. Blueberries were all over the place, and they got bigger as the rover went deeper—a sign of more groundwater deeper underground, which meant more hematite-producing chemistry.

From the bits of meteorite and ejected rocks strewn about from the original impact, the researchers deduced that the initial crater had been 600 meters wide and 125 meters deep. Over time, wind had widened the crater and blown sand into the bottom. The layering in the rock also suggested a windy past, and the variations in rock composition were similar to those found in Eagle and Endurance Craters, implying that the whole region underwent similar geological processes.

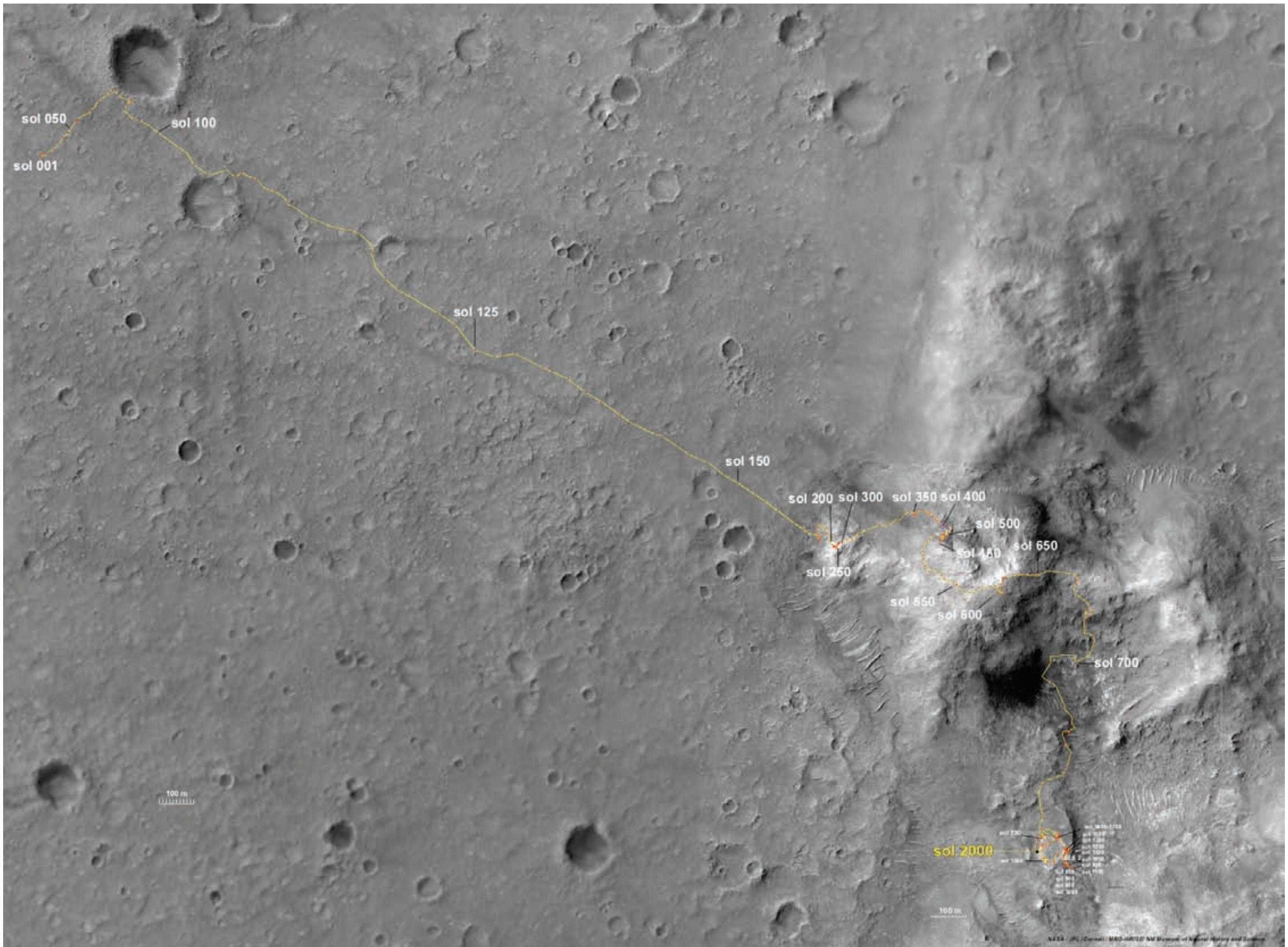
Then, some 1,500 days past the planned mission duration, Opportunity was still chugging along, so scientists set their sights on Endeavour Crater, a 22-kilometer-wide, 300-meter-deep behemoth roughly 17 kilometers away. As of this fall, the rover has been en route for about a year. There's still a long way to go, because engineers are rerouting the rover to avoid road hazards, such as other sand dunes similar to Purgatory (the team calls them "purgatoids"). These detours will add another 30 percent to the distance Opportunity will travel. On March 7, 2008, Opportunity caught its first glimpse of Endeavour's edge from 12 kilometers away.

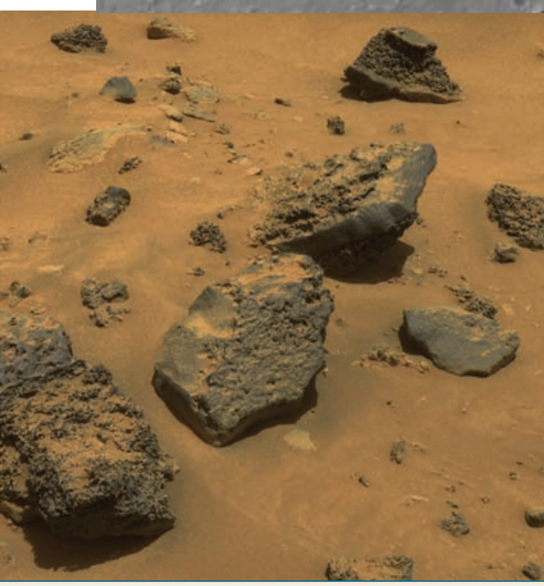
Throughout its journey to Endeavour, Opportunity has been looking at the soil and rock, mapping the changes in composition and chemistry. In late July, it took a picture of a dark, bluish rock the size of a big pumpkin that didn't quite match the other rocks in the area. Opportunity had already driven about 180 meters past the rock by the time the image, which was stored onboard for a few days, arrived on Earth. When the researchers saw the odd object, they turned the rover around and returned to take a closer look. Called Block Island, the rock turned

"When Spirit ended up on the lava plains, the team didn't give up on it," Zurek says. "It headed for the hills—literally."



Top: A promontory called Cape Verde at Victoria Crater. The wall is about 6 meters high.
Above: On March 7, 2009, Opportunity took a snapshot of the northern ridge of Endeavour Crater. This part of the crater is about 20 kilometers away.
Right: Block Island is the largest nickel-iron meteorite found on Mars.





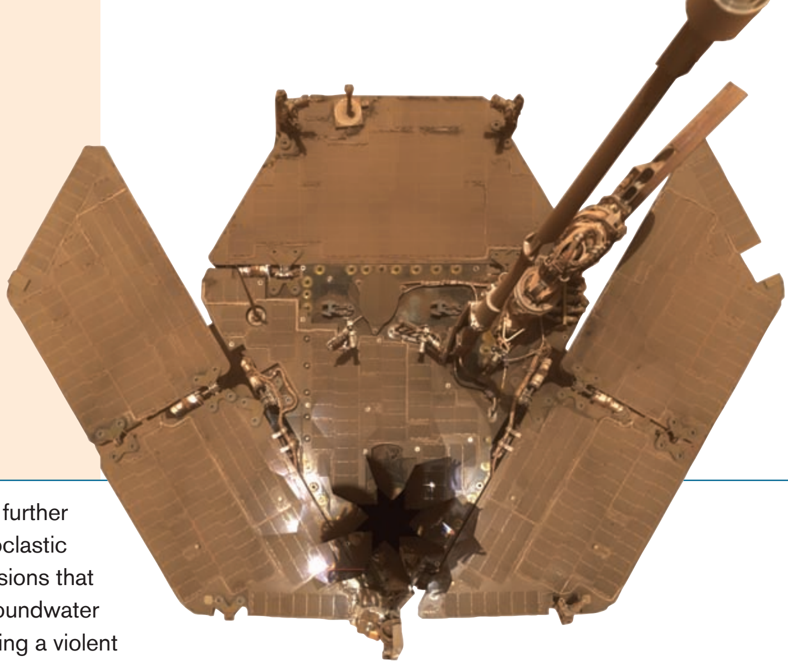
out to be an iron-nickel meteorite with a mass of about 500 kilograms—roughly ten times as massive as Heat Shield Rock.

THAT'S THE SPIRIT

On the other side of the planet, Spirit quickly overcame its initial software hiccup and has since made plenty of its own discoveries—although its path hasn't been nearly as smooth. The team had sent Spirit to what appeared to be a dried-up lake, but it proved to be a volcanic plain surrounded by lava rocks. "It was a bitter disappointment," Squyres says. The mission's goal was to look for signs of water, not magma. Most likely there were sedimentary deposits—just underneath the lava layer, beyond Spirit's reach. But then Spirit saw a potentially more interesting spot in the Columbia Hills, three kilometers away. "When Spirit ended up on the lava plains, the team didn't give up on it," Zurek says. "It headed for the hills—literally." Had Spirit been a lander, it would've been stuck with boring basalts. Had Spirit only lasted its planned lifespan, it would not have made it to the Columbia Hills, 156 sols into the mission.

The hills are named after the ill-fated space shuttle *Columbia*, and each of the

Top: Spirit's route from Gusev Crater to the Columbia Hills and Home Plate, near its current location.
Bottom: Scientists were hoping to find sedimentary rocks, which would harbor evidence of past water, at Spirit's landing site in Gusev Crater. Instead, the rover found a volcanic plain strewn with lava rocks.



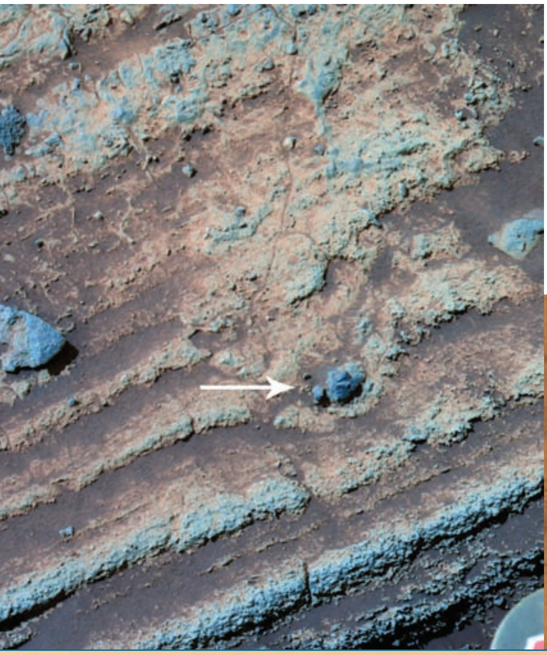
Exploring Mars can be a dirty job. The dust on Spirit's solar panels once caused power levels to dip dangerously low. Luckily, the rover was saved when some wind cleaned off the dust.

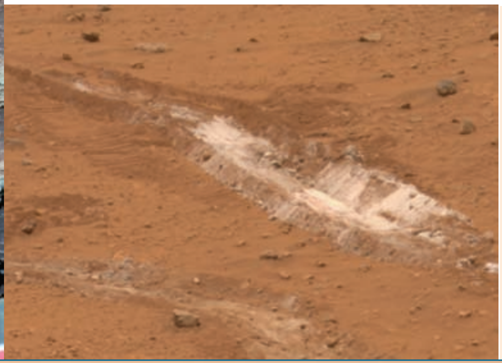
seven peaks bears the name of a crew member. Spirit arrived on June 16, 2004, and approached the region from the northwest, starting from the base and winding its way up and around the gentle slopes. The rover identified iron sulfate salts, a sign of groundwater. The team then drove it over to a 90-meter-wide plateau dubbed Home Plate, where Spirit has since spent the majority of its time. There, it has discovered a piece of volcanic rock embedded in the sedimentary layers. This kind of rock, called a bomb sag, becomes implanted after volcanic explosions have blasted it into the air and it lands in soft material—deformable dirt or maybe even mud. High concentrations of elements like chlorine, bromine, zinc, and germanium were further evidence for pyroclastic eruptions—explosions that happen when groundwater meets lava, creating a violent outburst of steam and flying rock.

In the spring of 2006, after about 800 sols on Mars, Spirit had descended from the top of Home Plate and started toward McCool Hill when its right front wheel jammed. Engineers spent weeks trying to fix it, to no avail. Spirit was now hobbled, but it could make do if it drove backward, dragging the lame wheel along behind it. It turned out, though, that the wheel would become a scientific tool. It carved a trench as Spirit rambled on, and in the summer of 2007, it uncovered a surprise—white soil that lay beneath the red surface.

The white stuff was amorphous silica, which precipitates from hydrothermal activity. These deposits don't form in days or weeks, but in anywhere from a few years to a few thousand years, says Diana Blaney, the MER deputy project scientist. Evidently, Mars may once have been home to hot springs, and if they're anything like the ones on Earth (in Yellowstone National Park, for example), they can be abodes for all sorts of life. There has been other evidence for such mineral spas. In 2008, the Mars Reconnaissance Orbiter's high-resolution camera took snapshots of Vernal Crater in Arabia Terra, and found mounds and channels that looked like those made by hot springs in Yellowstone.

Finding silica was serendipitous, but Spirit also needed luck just to survive. Earlier, less than 400 sols into the mission, the rover had run dangerously low on power when dust blanketed the solar panels. At peak performance, Spirit could generate 900 watt-hours of energy per day, but now it was down to 300 watt-hours. If production dropped to 200 watt-hours, the rover would die. Luckily, Mars appears to have a natural





Far left: A bomb sag. When lava meets steam, an explosion blasts volcanic rock into the air, and it falls and becomes embedded in the ground.
Left: Spirit's defunct wheel dug up amorphous silica from under the surface—evidence for hydrothermal vents.
Below: The Columbia Hills from a couple kilometers away.

vacuum cleaner—not a Dirt Devil but maybe a dust devil, or simply a gust of wind—that blew off the dust, returning energy production to 850 watt-hours. Spirit was up and moving again—that is, until May of this year, when it got stuck in a place called Troy, west of Home Plate.

According to John Callas, MER project manager, Troy is a fascinating site, with layered terrain chock full of sulfates and amorphous silica. Researchers still don't know how old these minerals are, Callas says, and there's a possibility they could have a relatively recent origin. Now, while the engineers work to get Spirit out, the rover is still busy doing science, analyzing the soil and silica deposits around it, trying to glean as much information as it can. As Zurek says, "We're literally just scratching the surface of understanding the history of the planet."

ROVING INTO THE FUTURE

In 2011, NASA will launch the Mars Science Laboratory (MSL). Now also known as Curiosity, MSL is the next-generation rover, a bigger vehicle that will be better equipped to analyze Martian chemistry and further gauge the planet's habitability for life. MSL will have instruments that can identify organic compounds, and instead of relying on solar panels and the occasional Martian wind to keep them clean, MSL will use a chunk of plutonium to power its year-long mission. After MSL comes Maven, an orbiter that will study Mars's upper atmosphere. Planned for launch in 2013, Maven got the go-ahead from NASA last fall.

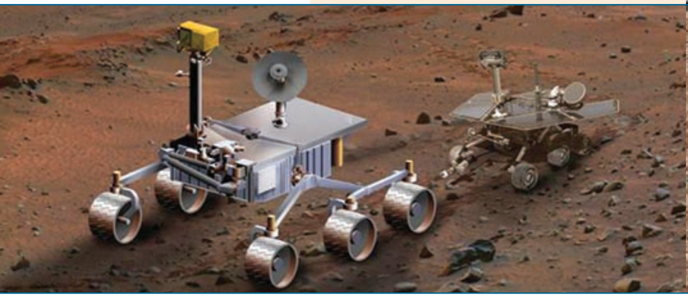
Eventually, researchers hope for a sample-return mission. Even with improving technology, a rover can't replace a laboratory on Earth. Some experiments—such as accurate radiometric dating to establish a chronology of Mars, which is still a major source of uncertainty—require elaborate sample preparation or instruments too heavy to put on a rocket. With Martian rocks on hand, scientists can get immediate results on follow-up experiments without having to send another spacecraft to find out more, Zurek explains. "In a way, sample return replaces multiple missions."

Spirit's and Opportunity's wheels just keep spinning. "The ability to go several kilometers is what has set them apart," notes Zurek. They have also proven that you can't fully understand Mars unless you're on the ground, digging in the dirt. Otherwise, researchers would never have been able to identify the blueberries, discover silica deposits, explore the Columbia Hills and the Meridiani craters, or find meteorites. Other NASA spacecraft have also lasted far beyond their design lifetimes—Voyagers 1 and 2, for example, have been zipping through space for more than three decades and are now beyond the orbit of Pluto. But vehicles roaming the surface of other planets are another matter. Daily temperature swings of over 100 degrees torture electronics, because the cycles of hot and cold can snap delicate connectors, and dust and grit can jam joints and wheels.

Despite their durability, the rovers are showing signs of age. Spirit once ignored its morning wake-up call last spring, and has occasionally rebooted its computer

Right: An engineering prototype of the Mars Science Laboratory tests its wheels on a mock Martian surface at JPL.

Below: A rendering of MSL and Spirit showing their relative sizes.



for no known reason. Periodic dust storms have covered both rovers' solar panels with dirt, requiring more wind cleanings. In April, Spirit's power production once again dipped to 240 watt-hours per sol before the winds came. Eventually, the mission will end—either mechanical parts or software will break down, or the Martian wind won't come to the rescue in time. "We're way past the warranty on these things," Blaney says. But "they'll keep going until stuff breaks."

As of now, Opportunity is continuing its journey to Endeavour Crater, and engineers are hopeful that they will free Spirit soon. But whatever their fates, the twin rovers have already made their mark. "We'll always have a special place in our exploration hearts for those two vehicles," Zurek says. "Even as we come up with more sophisticated and bigger ones in the future, these are the ones that showed us we could get around and find things—and that's pretty powerful." e&s

PICTURE CREDITS

12 — NASA/JPL/UA; 13-14, 19 — NASA/JPL/Caltech; 14 — NASA/JPL-Caltech/Cornell/Ohio State Univ./MSSS/Univ. of Arizona; 13-18 — NASA/JPL-Caltech/Cornell; 17 — NASA/JPL/Cornell/MRO-HiRISE/NM Museum of Natural History and Science; 18 — NASA/JPL-Caltech/USGS/Cornell; 20 — Jim Bell/AURA/STScI/NASA

WHY MARS?

In recent years, other planetary bodies have grabbed headlines. Enceladus, one of Saturn's moons, has towering, water-rich geysers. Saturn's biggest satellite, Titan, hides liquid-ethane seas under its thick methane atmosphere. Jupiter's moon Europa is thought to harbor an ocean below its icy surface. These discoveries point to a newfound potential for life on the moons of the outer planets, and with such diverse environments, these places would seem to be the next frontier in solar-system exploration. If that's the case, why are we still going to Mars?

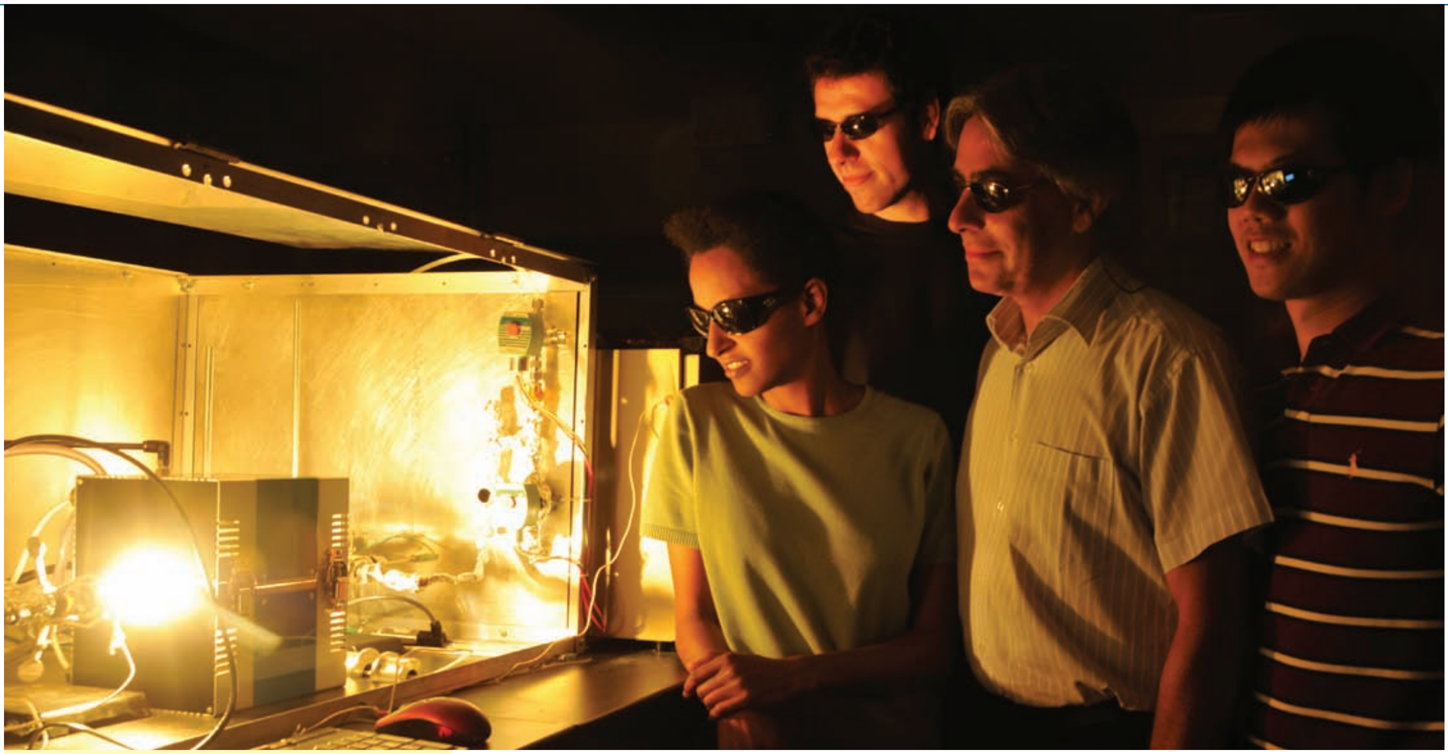
One simple reason is that it's close, Blaney says. While it takes 6 to 10 years to go to the outer solar system, we can get to Mars in six months every couple of years when it aligns with Earth. Being a rocky planet, it's also easier to explore. To get to Europa's subsurface ocean, for example, you would have to drill through kilometers of thick ice. And unlike on Venus with its thick, heat-trapping clouds, spacecraft don't melt on Mars.

Furthermore, much of Mars's history mirrors that of Earth, and because it's now much less geologically active than Earth, its surface hasn't been erased by earthquakes, volcanoes, and drifting tectonic plates, Zurek explains. Studying Mars, then, is like looking at Earth's past. Mars could hold insights into our history that are not found elsewhere in the solar system.

Beyond the science, Mars has always had a certain allure. "It has a psychological accessibility that makes the public see it differently from the rest of the solar system," Zurek says. With canyons, mountains, wind, ice, clouds, and even snow, Mars is similar enough to Earth that we can envision walking there. "It's hard to think of astronauts being on Io, Europa, or Venus," he says. At the same time, Mars still has an alien appeal. In 2004, President Bush outlined a plan to send humans to Mars. Whether or not the American space program will indeed go in that direction remains to be seen. In September, the U.S. Human Space Flight Plans Committee, a congressionally appointed panel of experts charged with assessing the program, issued a summary report that says there isn't enough money allocated to send humans to the moon and Mars. "The U.S. human spaceflight program," the summary reads, "appears to be on an unsustainable trajectory." But regardless of whether we explore it in person or by proxy, Mars is still capable of stirring anyone's adventurous spirit. e&s

Put Some Sunlight in Your Tank

by Douglas L. Smith

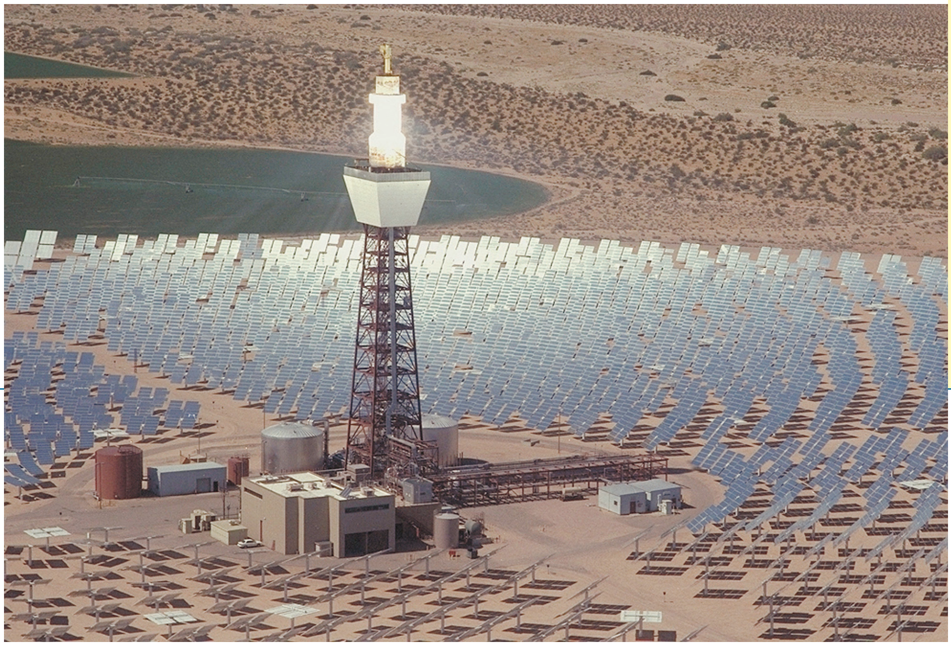


Carbon-neutral doesn't need to be carbon-free. Green plants make fuel from sunlight and carbon dioxide—can we make gasoline the same way? It would certainly be a lot simpler than replumbing the planet to run on compressed hydrogen.

You know what would be really cool? A gadget that turns carbon dioxide into gasoline. And while we're at it, let's make this gizmo solar powered. It's a great daydream, and grad student William Chueh (BS '05, MS '06), in Professor of Materials Science and Chemical Engineering Sossina Haile's lab, has taken the first steps toward making it happen.

As you may have heard, humanity's reliance on burning coal, oil, and other fossil fuels has helped raise atmospheric carbon dioxide levels from 285 to 385 parts per million by volume over the last century, with no end in sight. The alterations to the world's climate likely to result are widely considered to be a bad thing, except perhaps in Alaska. As a civilization, we currently consume 16 trillion watts, or terawatts, of energy. If we are to rein in CO_2 at 550 parts per million, which is thought to be the prudent upper limit to avoid irreparable harm, we are going to need 20 terawatts of carbon-neutral energy by the year 2050. But being carbon neutral doesn't necessarily mean we have to be completely carbon-free. If we could use

The future's so bright they have to wear shades. . . . From left: Sossina Haile, Christoph Falter, Aldo Steinfeld, and William Chueh bask in the glow of the high-temperature furnace that simulates concentrated sunlight for the CO_2-to-solar-fuel studies.



The Department of Energy's Solar Two demonstration plant, just east of Barstow on the outskirts of Daggett, California, used motorized mirrors called heliostats to focus sunlight on a collector atop a 90-meter tower. Fourteen hundred tons of molten salt were pumped through the collector, heated to 565°C, and stored in an insulated tank at the tower's base. The hot salt was used to make steam that ran a turbine, producing enough electricity to power 10,000 homes for as long as three hours after sunset. The project ran from 1996 to 1999. Plants now under development can store enough salt for up to 15 hours of power.

the same carbon atoms over and over again, turning the CO_2 from burning hydrocarbons back into hydrocarbons that we could burn again, we would come out even in the global sense.

Unfortunately, turning carbon dioxide back into hydrocarbons is very, very hard. The world's worth of energy that we get out of hydrocarbons comes from forming carbon-oxygen bonds, and we'd need to pump all that energy back into the bonds in order to break them. That's why carbon dioxide doesn't go away by itself once it's been released into the atmosphere. "Breaking CO_2 apart is an uphill struggle," says Haile. "It's like hiking from Pasadena up into the San Gabriel Mountains to Charlton Flats. And worse, if you make a beeline for Charlton, you have to climb Mount Harvard and Mount Wilson in the process. It takes a top-notch catalyst to insert the necessary energy into the bonds, especially at room temperature, or in other words to find a trail that goes around the mountain peaks."

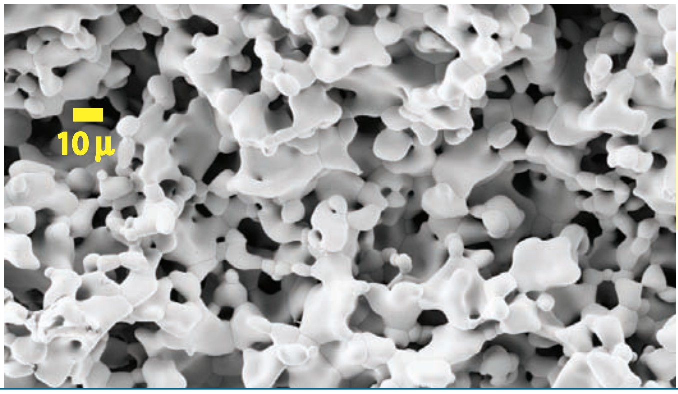
While green plants use cheap, readily available materials to make a woefully fragile but marvelously efficient manganese catalyst, we humans have had less luck at using sunlight to convert CO_2 into fuel. It is so hard, in fact, that most scientists have opted to take another approach to the solar-fuel problem, focusing on splitting water to make H_2. The hydrogen-oxygen bond is easier to break, but even that requires rare, expensive metals such as platinum. (See *E&S* 2008, No. 2, and 1997, No. 3.) Says Haile, "So we asked ourselves, if inserting the energy from sunlight into the chemical bonds of CO_2 is so hard, is there another route? And the answer is to use the sun's heat. The heat lets the reaction take an easier path around the mountains, and because everything moves faster at higher temperatures, we get the added bonus of producing the fuel very quickly."

The catch is that when Haile says "higher temperatures," she means *really* higher temperatures—an incendiary 1,500°C, hot enough to melt steel. This doesn't bode well for designing a device that you can bolt to the muffler under your minivan.

The work was inspired by tailpipe technology, however. For the last eight years, Haile's lab has been working with cerium oxide, CeO_2, or "ceria," which is the key ingredient in the lab's family of solid-oxide fuel cells. (See *E&S*, 2008, No. 2 and 2003, No. 1.) To the rest of us, however, ceria is best known—if we've heard of it at all—as the main ingredient in our cars' catalytic converters. There, CeO_2 acts as an oxygen-transfer system. It grabs the oxygen atoms from the smog-causing NO_x molecules in the exhaust, reducing them to harmless nitrogen gas, and then turns around and donates the seized oxygen atoms to passing carbon monoxide molecules, transforming deadly CO into CO_2.

Chueh's project goes the other way, converting carbon dioxide and steam to a mixture of H_2 and CO known as "synthesis gas," or "syngas" for short. From there, you can make pretty much any hydrocarbon—including gasoline, diesel oil, and jet fuel—via the Fischer-Tropsch process, which was invented by Franz Fischer and Hans Tropsch at the Kaiser Wilhelm Institute in Berlin in the 1920s. Nazi Germany, cut off from most of the world's petroleum reserves, used the process to convert its abundant coal supplies into liquid fuels during World War II; South Africa got around the oil embargo of the apartheid years in the same way. It would be ironic indeed if a technology with roots in such evil empires wound up doing a world of good, but history is a notorious practial joker.

Today, South Africa still makes most of its diesel fuel using the Fischer-Tropsch process. And, concerned about future fuel supplies, the Department of Defense is working with a firm called Syntroleum to have every plane in the Air Force certified



The ceria powder used in these experiments is extremely porous on the microscale, providing plenty of surface area for the reactions to occur. The scale bar is 10 microns, or millionths of a meter, in length.

to fly on a 50-50 mixture of jet fuel and a Fischer-Tropsch product by 2011.

Getting 1,500-degree temperatures from concentrated sunlight is not a cakewalk, but it has been done. Solar-thermal electric-power plants use arrays of pivoting mirrors to track the sun and focus its light on fluid-filled tubes. The superheated fluid can be piped to the turbine room to make electricity straight away, or it can be stored in insulated tanks for use after dark. A handful of commercial plants are already online in sun-drenched parts of the world, most notably the Nevada Solar One project near Boulder City and the Solúcar complex near Seville, Spain. And huge plants are planned for the Mojave Desert as California's utility companies scramble to meet the state's 20 percent renewable-energy standard that kicks in in 2010. These solar-electric plants operate at somewhat lower temperatures than are needed for the ceria-based process, but with some tweaking the concentrator technology could be adapted.

But there's no need to get riled up about the potential environmental impacts of installing square miles of mirrors in the desert. The ceria system can make syngas from the stuff that goes up the boiler-house smokestacks at coal-fired power plants. This flue gas is about 20 percent CO_2 and 10 percent H_2O, with the rest being N_2 from the air. Says Haile, "In a coal-fired power plant, the biggest cost when people think about sequestering the CO_2 is separating it from the N_2. But we don't have that worry. The nitrogen does not affect our process."

So if we continue to make electricity from coal—which is cheap and abundant, and we're therefore probably not going to stop any time soon—and then we make gasoline or jet fuel from the flue gas, we'll at least be using each carbon atom twice. At 2006 emission rates, this translates into preventing some two billion metric tons of carbon dioxide from escaping into the atmosphere from the United States alone. Converting that CO_2 back into hydrocarbons would meet the nation's petroleum needs of 14,000,000 barrels per day and "essentially eliminate the transportation sector as a CO_2 source," says Haile.

BREATHING DEEPLY

The carbon-dioxide-to-fuel conversion process hinges on bulk ceria's ability to lose lots of oxygen atoms without altering its crystal structure. When heated to 1,500°C under an inert flow of nitrogen gas, CeO_2 can surrender as much as 2.5 percent of its oxygen content, a process Haile and Chueh call exhaling. "Everyone needs to say they do something with biology these days," Haile laughs. "This is as close as I get. I have metal oxides that breathe. And like biology, we're making carbon-containing compounds from the sun." At such high temperatures, most metal oxides would collapse into other crystal forms that filled the vacated spots; keeping the voids open allows the oxygen-depleted ceria to hold its breath while it gets cooled to a mere 900°C. Then the flue gas is piped in, and the suffocating ceria gulps down all the oxygen it lost, stripping CO_2 to CO and H_2O to H_2—syngas!

Experiments done in a benchtop furnace the size of a toaster oven show that both of these steps work quite well. The finely powdered, highly porous ceria is placed in an alumina tube through which a test gas mixture is blown. The gas coming out of the tube's far end is analyzed in a mass spectrometer and a gas chromatograph, which identify the molecules in the gas stream and measure their concentrations.

In the first step of the process, where the ceria exhales, the oxygen release "is very close to our thermodynamic prediction of around 3.5 milliliters per gram of ceria," says Haile. "And because our furnace gets to high temperatures almost instantaneously and the ceria has such a phenomenal response, we see that 90 percent of that oxygen is released in less than two minutes."

On the other half of the cycle, the fuel-production end, Chueh started by testing water vapor and carbon dioxide separately, by letting the ceria exhale and cool before piping one of the two gases into the 900°C furnace. He found that he got all the hydrogen out of the water—the theoretical maximum of about seven milliliters per gram of ceria—in the same two to three minutes. Ditto for the CO. Says Haile, "We are now able to produce CO from CO_2. And by the way, that means we have a lot of good carbon-monoxide sensors in our lab."

Chueh then tried a flue-gas stand-in, a 2:1 mixture of dilute H_2O and CO_2 in nitrogen, on the blue-faced ceria. He got 100

If we continue to make electricity from coal—which is cheap and abundant, and we're therefore probably not going to stop any time soon—and then we make gasoline or jet fuel from the flue gas, we'll at least be using each carbon atom twice.

Opposite: The solar furnace at the Paul Scherrer Institute. The heliostat, seen from the rear, directs sunlight onto the parabolic mirror in the building in the background. The front of the building is a giant set of venetian blinds used to regulate the intensity of the solar flux. The furnace is capable of generating temperatures in excess of 3,000 kelvins at heating rates of more than 1,000 kelvins per second.

percent conversion to syngas—a 2:1 mixture of H_2 and CO out the other side—again, in under two minutes. This equates to 0.2 liters of the mixture per gram of ceria per hour. Says Chueh, "The record production rate for hydrogen is on the order of 10,000 microliters [0.01 liters] per hour per gram, whereas for CO_2, the highest is only on the order of 160 microliters, using platinum and copper catalysts on titania." Says Haile, "Our fuel production rate is 200,000 microliters per hour per gram of material. We have to convert into units of microliters, because this is what other groups typically report, and we are at *liters* per gram per hour. So that's the benefit of being at a high temperature. Things just proceed much more quickly."

FROM SYNGAS TO NATURAL GAS

Chueh didn't need nickel to get phenomenal reaction rates, but since nickel is known to catalyze the breakdown of CO_2, he decided to try adding some to see if he could manipulate the outcome of the dissociation reaction. Normally, he explains, "When you break the carbon-oxygen bond, the carbon does not like to reside on the ceria. It absolutely hates it. So that means that we cannot split CO_2 to the thermodynamic limit, which is pure carbon, and we get CO instead. We can't break the carbon's triple bond to the oxygen in carbon monoxide. Energetically, forming solid carbon is favored, but we just can't get there kinetically." As Haile is fond of saying, "Thermodynamics tells you what *can* happen, not what *will* happen." In terms of the cross-country hike to Charlton Flats, the kinetic route is the one that takes you over the summit of Mount Wilson. If you don't have a catalyst that knows the thermodynamic trail that winds along the lower elevations of the canyon floors, and you don't feel energetic enough to tackle the steep slopes, you'll say the heck with it and stay home.

After Chueh added nickel particles to the powdered ceria, "when we put pure CO_2 in, *nothing* came out. Nothing. When the ceria inhaled the oxygen, all that was left of the CO_2 was some solid carbonaceous species. When we took the powder out of the tube to look at it, it was just coated with graphite. You could write with it. We found that if you add nickel, all the carbon resides on the nickel. The ceria still can't take any carbon, but the nickel can." With elemental carbon now available on the nickel, a whole new set of possible reactions opens up. If you add water vapor, you can make methane, CH_4, aka natural gas—another fuel that's pipeline-ready. And indeed, blowing the mock flue gas through the nickel-ceria mixture produced methane.

Better still, with the nickel catalyst you can tune the system to choose your product. When you process flue gas at lower temperatures, around 400°C, the nickel catalyst enables the thermodynamic pathway to compete with the kinetic one, and methane production predominates—up to 80 percent methane under the right conditions. As the temperature increases, the kinetically favored reaction takes over, and by 700°C the methane is gone and you're back to pure syngas. "We're not making policy choices," Haile says. "We're giving the policy makers technological options."

With making natural gas now an option, a solar-thermal ceria plant could be operated the way that windmill farms are, Haile says. "Many wind farms are co-sited with natural-gas-fired power plants. During the daytime, a solar farm would provide electricity, but we'd simultaneously generate natural gas. The co-sited natural-gas plant—or better yet, a fuel-cell power plant—would operate on rainy days and at night, or to compensate for variations in demand, and we'd cycle the waste CO_2 back into the solar-thermal plant."

TAKING IT OUTDOORS

By Haile's calculations of how much sunlight it would take to get the ceria up to 1,500°C, "we end up with about 13 percent efficiency. Photovoltaics started off with a fraction of a percent, and now you can go out and buy ones that are on the order of 13 percent efficient in producing electricity. So this is not bad." And there is plenty of room for improvement—as the ceria breathes, there's a temperature swing of 600°C to 1,100°C, depending on which fuel you're making. That's an awful lot of waste heat to get rid of during each cooling cycle, so any practical system would need to capture and reuse as much of that energy as possible. "If we could come up with some scheme to recover half of that heat, then we would

Says Haile, "Our fuel production rate is 200,000 microliters per hour per gram of material. We have to convert into units of microliters, because this is what other groups typically report, and we are at *liters* per gram per hour."

increase the overall efficiency to about 23 percent," Haile says. "And that gets to be really quite attractive."

Haile's lab is collaborating with Aldo Steinfeld, a professor at the Swiss Federal Institute of Technology (ETH) in Zürich and head of the Solar Technology Laboratory at the Paul Scherrer Institute. Steinfeld, who is on campus through December as part of a sabbatical in the States, has been in the high-temperature solar-fuel hunt since the early '90s. In 1997, his lab fired up a solar furnace capable of producing 5,000 kilowatts per square meter, that is, the flux intensity of 5,000 suns. The unit looks rather like a giant headlight aimed across a grassy lawn at a drive-in movie screen. The movie screen is a rectangular heliostat—a pivoting 12-by-10-meter mirror that tracks the sun and throws its light onto an 8.5-meter-diameter parabolic reflector that in turn is focused on a reaction vessel roughly the size of an oil drum.

The reactor now occupying the focal point splits water into H_2 and O_2 in a two-step thermochemical cycle based on a zinc catalyst. Steinfeld and his grad student Christoph Falter, who came to Caltech with him, are designing a three-kilowatt apparatus for the ceria process. "In contrast to the zinc-based system, where zinc oxide thermally dissociates into zinc vapor and oxygen, the ceria remains in solid form throughout. So we need an entirely different reactor concept," says Steinfeld. The prototype will be a cylinder about 20 centimeters in diameter by 20 centimeters long, or somewhat larger than a gallon milk jug. The concentrated sunlight will be focused on a quartz or sapphire window in one end of the reactor's cavity. The cavity will act as a black-body absorber, soaking up all the energy and transferring it to the porous ceria monoliths—a fancy word for bricks—within.

The plan is to ship the setup to Zürich in December. "The goal is to demonstrate an integrated solar-reactor technology with the ceria-based thermochemical cycle," says Steinfeld. "It's an ambitious goal—we basically need to operate a mini thermochemical plant with concentrated solar energy." Haile adds, "We need to maintain very high temperatures in the cavity while keeping everything gas-tight. We also have to cycle

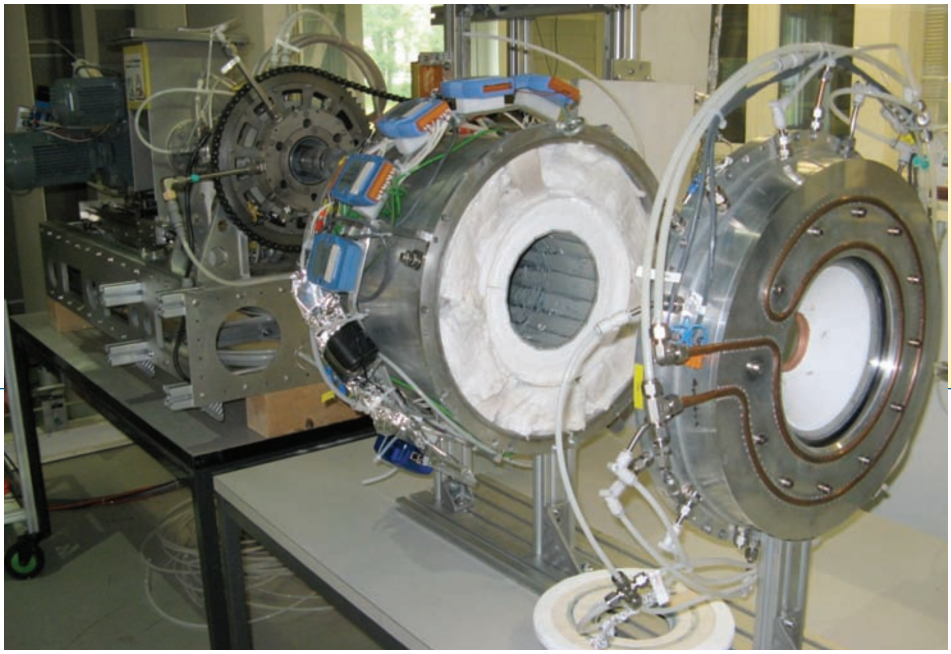
THERE'S PLENTY OF ROOM UNDER THE SUN

Solar-thermochemical fuel production is a hot research topic. The Sandia National Laboratory in Albuquerque, New Mexico, has a solar reactor designed to turn CO_2 into CO, while the University of Colorado at Boulder is working on a project to turn biomass, such as corn stalks, into syngas.

On the water front, Jane Davidson of the University of Minnesota is collaborating with Steinfeld on the zinc-based water splitter. The Weizmann Institute of Science in Rehovot, Israel, has a zinc system of its own, while the DLR, the German space agency, is developing a system based on iron oxides. And in Japan, Niigata University and the Tokyo Institute of Technology are working on mixed metal oxides based on iron, nickel, and cobalt.

The French national research agency, CNRS, has a one-megawatt solar furnace at Odeillo, a ski resort in the Pyrenees; across the border in Spain, CIEMAT, the Spanish national energy reseach institute, has a solar tower at Almería, on the Mediterranean.

"Solar-thermochemical fuel systems can use the concentrator technologies now being deployed for large-scale solar-thermal power production, and thus have the potential to be economically competitive," says Steinfeld. E&S



Steinfeld's 10-kilowatt zinc reactor operates at 2,000 kelvins. In the middle of the picture is the rotating reaction cavity, where the zinc oxide particles are held against the heavily insulated chamber wall by centrifugal force. The concentrated sunlight enters through the quartz window on the right, inside the copper C of cooling-water lines.

the system between the two temperatures very rapidly, and we have to guard against solar leakage, so that we focus the sunlight where we want it, and not where we don't. There are a lot of things that have to happen correctly, and we are really relying on Aldo's experience to help guide us through the design and construction."

Chueh will accompany Falter back to Switzerland for the reactor studies. Chueh did an exhaustive kinetic and thermodynamic analysis as part of his PhD. As part of his own thesis, Falter is developing a comprehensive heat- and mass-transfer model of the entire process in parallel with working on the reactor design. If the experiments are successful, and the model measures up, the next step will be to use it to optimize the reactor configuration for maximum solar-energy-to-fuel conversion efficiency. Then, says Steinfeld, "We would like to scale it up from kilowatts to megawatts."

"Certainly many challenges remain," says Haile. "We're just getting started. We'd like better lungs on our ceria, which would give us higher efficiency, higher fuel productivity, and lower cost. But precious-metal catalysts have really been the stumbling block for most of the ways of generating fuels from the sun. Cerium is as abundant as copper. The total world reserves are on the order of 40 megatons—some 15 percent of it right here in California—and we estimate that if we had 100 cycles a day running under optimal conditions, and we produced enough fuel to operate for six more hours after dark, there's enough ceria to run about 140,000 one-hundred-megawatt power plants. That's not bad. It's 14 terawatts at nighttime or, in terms of total energy consumption in terawatt-hours, it's nearly 20 percent of the clean energy that we're going to need by 2050. Making gasoline from sunlight is all very well, but what I find personally much more exciting is using our process to store solar energy at a power plant, for generating electricity when the sun isn't shining. Right now, a national consensus is building that we can't provide more than about 20 percent of our electricity from renewable sources until we have solved the storage problem. Maybe, just maybe, this will be the key to getting us to 100 percent." e&s

Sossina Haile got her BS and PhD from MIT (the latter in 1992), with a side trip out west for an MS at UC Berkeley. She came to Caltech in 1996, after three years as an assistant professor at the University of Washington in Seattle.

A paper describing this work appeared online in ChemSusChem, the journal of chemistry and sustainability, on July 27. (See.)

***Chueh presented his results at the first annual $30,000 Lemelson-Caltech Student Prize competition, awarded to an undergrad or graduate student "to recognize and inspire . . . burgeoning innovators and inventors," and funded by the Lemelson-MIT Program and Michael W. Hunkapiller (PhD '74). Chueh won $10,000 as runner-up to Ophir Vermesh, a grad student of Gilloon Professor and Professor of Chemistry James Heath. Vermesh's work was described in the Winter 2008 issue of* E&S.**

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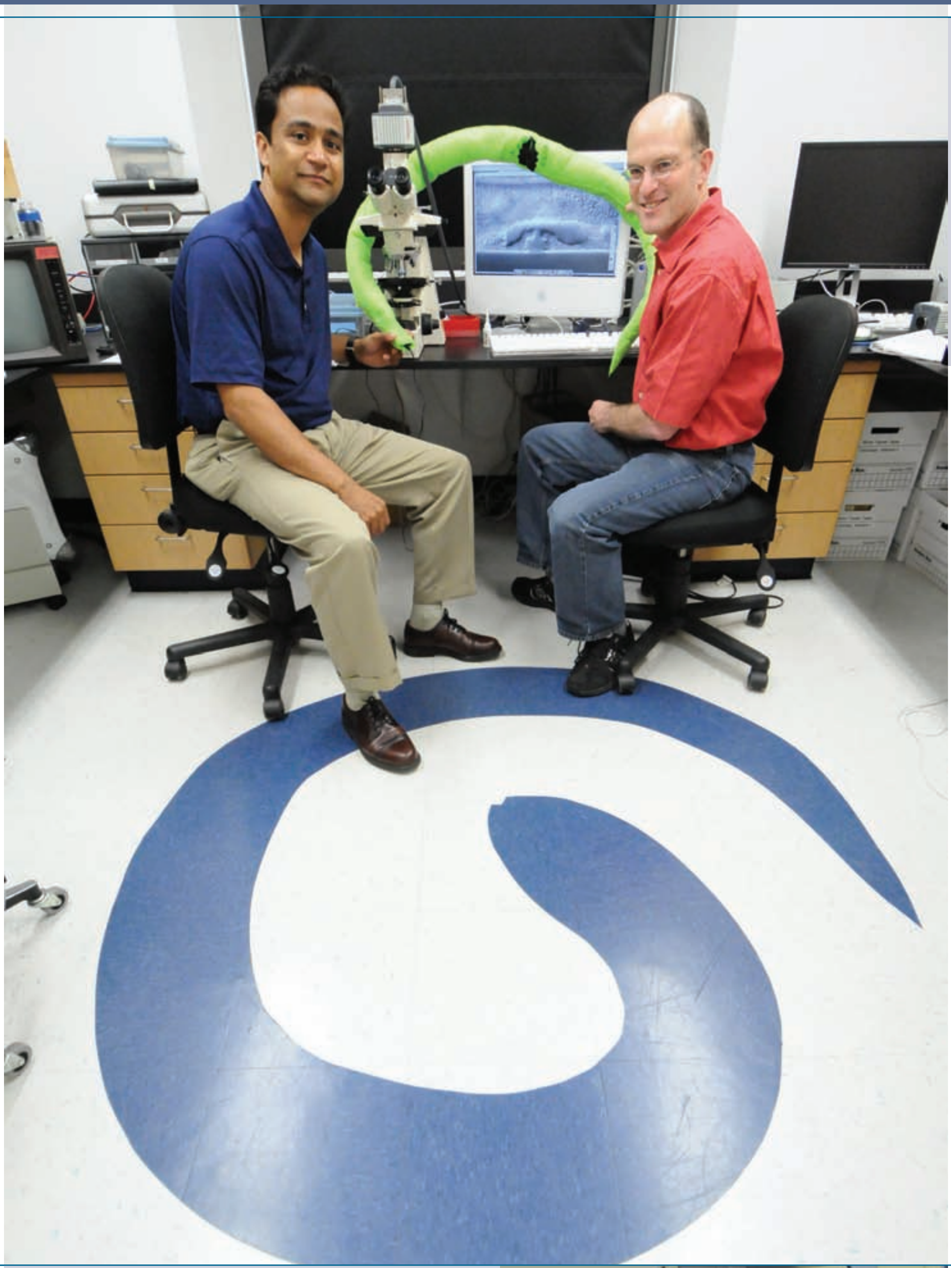
PICTURE CREDITS
21 — Bob Paz; 22 — Department of Energy; 23 — William Chueh; 25, 26 — PSI/ETH

"Making gasoline from sunlight is all very well, but what I find personally much more exciting is using our process to store solar energy at a power plant, for generating electricity when the sun isn't shining."

On the (Molecular) Origin of Species

By Douglas L. Smith

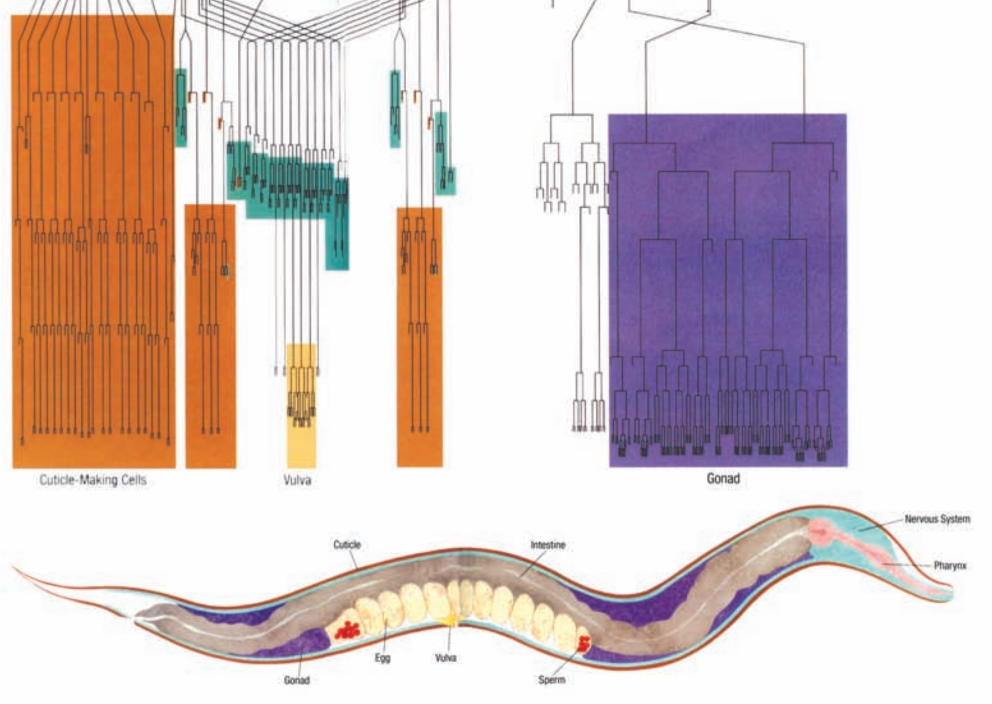


How does a species get the ball rolling when it's time to evolve? The change has to begin somewhere, and studying a tiny worm may show us the source.

When Charles Darwin visited the Galápagos Islands in 1835, he beheld many strange and wonderful creatures found nowhere else. He also collected a variety of small birds—some with long, pointed beaks for supping from cactus flowers, others with deep, wide beaks for crushing seeds, and still more with beaks of intermediate sizes for eating insects or fruit. Poring over his specimens later, he realized that they were all finches, and would write in *The Voyage of the Beagle*, "One might really fancy that, from an original paucity of birds in this archipelago, one species has been taken and modified for different ends." The finches steered Darwin to the idea of evolution by natural selection, and in November 1859 he would publish *On the Origin of Species*.

Now, on the sesquicentennial anniversary of Darwin's masterwork, we are on the verge of figuring out the molecular basis for species diversity. For example, scientists at Harvard and Princeton have discovered two signaling proteins that shape birds' beaks. Plying chicken embryos with too much of one protein produced hatchlings with long,

Above: Asthagiri (left) and Sternberg (right) in the Caltech nematode lab (note the floor tiles) with a five-foot-long, anatomically correct stuffed roundworm. The vulval cells are the black felt appliqué. Right: Giurumescu is now a postdoc in Andrew Chisholm's nematode lab at UC San Diego.



This color-coded map traces the family tree of each of *C. elegans*'s 959 body cells back to the fertilized egg. Each horizontal line represents one round of cell division. The length of each vertical line is the time between divisions. In the normal worm, every cell always divides in exactly the same way at exactly the same time, and every cell always assumes exactly the same position and exactly the same function in the adult worm—exactly 302 cells make up the nervous system, for example.

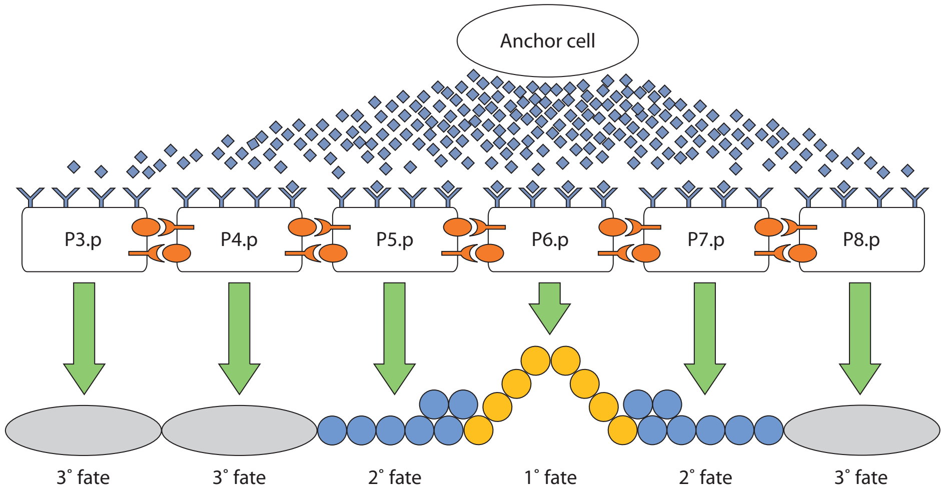
slender beaks like the cactus finches; an oversupply of the other led to poultry with broad, oversized bills. In a normal chick, the two proteins are in balance, so how does nature nudge them apart? Everything has to start somewhere, and the answer may lie in a mathematical model created at Caltech by then-graduate student Claudiu Giurumescu (PhD '08) when he applied a handful of differential equations to a tiny, transparent, soil-dwelling roundworm. It turns out that there is hidden variability in the network of molecules that determines what each cell in the worm becomes, even though its development is controlled with the mechanical precision of a self-winding Rolex. (The paper appears in the April 10, 2009, issue of *PLoS Computational Biology.*)

This worm, a nematode called *Caenorhabditis elegans*, is about the size of the comma that follows its name. *C. elegans*, as it is affectionately known, is right up there with the fruit fly in developmental biology's stable of model organisms. Its short lifespan and transparent body have allowed scientists to track each individual cell as it sprouts forth, from the single-celled egg through the larval stages to the 959 body cells of the mature adult. Beginning in the mid-1970s, generations of grad students—including Paul Sternberg, now Caltech's Morgan Professor of Biology and an investigator with the Howard Hughes Medical Institute—spent their academic careers hunched over microscopes, straining their eyes at squirming squiggles, painstakingly tracing the pedigree of each cell one division at a time. They found that the process is genetically hardwired—absent intervention by inquisitive biologists, those 959 cells will appear in the same place and in the same order in each and every worm.

In the 1990s, the worm's full genetic code was deciphered—the first multicellular species to have that honor—and a loose collaboration of research groups sprang up around the world to work out what every protein specified in the code does. Many of these proteins proved to be signaling molecules that coordinate the construction of the worm by telling cells when to divide and what to become—nerve, muscle, intestine, or what have you.

Over the last 20 years, Sternberg's and other labs have charted the entire network of proteins involved in creating *C. elegans*'s vulva, the opening in the skin that leads to the ovaries. The budding vulva is ideal for this, because you can tamper with the signaling molecules to your heart's content without lethal consequences. (A vulvaless worm will grow up just fine, but try raising nematodes without digestive tracts.) And

The nematode's vulva begins to form when the anchor cell in the worm's developing uterus begins secreting a molecular signal (blue diamonds) that diffuses away into the intercellular fluid. This molecule binds to receptors on the surfaces of six cells, numbered P3.p through P8.p. The closer the cell is to the anchor cell, the stronger the signal. This, plus a second signal (orange) between adjoining cells, tells each cell whether its progeny should form an opening (1° fate, yellow), a lip (2° fate, blue), or part of the surrounding tissue (3° fate, gray).



the mutants obligingly reproduce, even vulvaless ones, sparing the researchers the necessity of having to reinduce the same mutation in fresh worm eggs every few days. *C. elegans* is hermaphroditic, having both male and female sex organs, so a worm can fertilize its own eggs internally. They hatch and grow inside the body, and if their exit is blocked, they eventually make their way out in a manner reminiscent of Kane's gory dinner-table demise in *Alien*.

BUILDING A BETTER MODEL

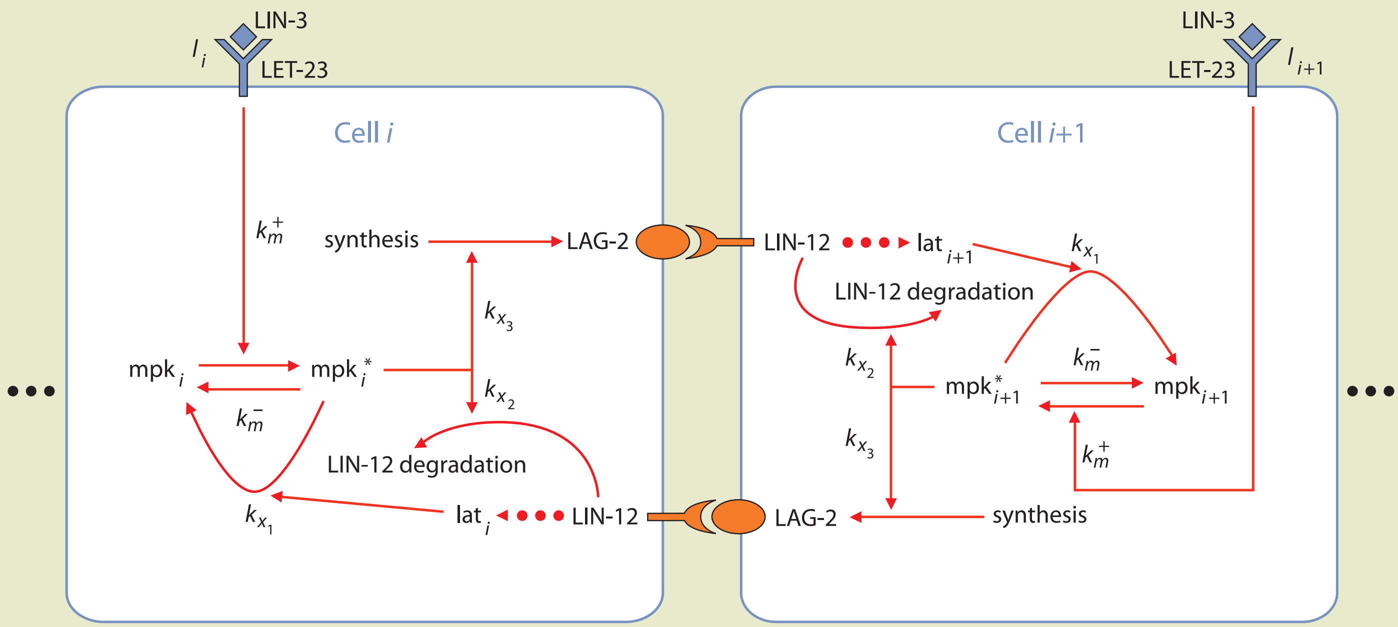
Giurumescu didn't set out to monkey with roundworms. His PhD advisor was Assistant Professor of Chemical Engineering Anand Asthagiri, whose lab specializes in tissue engineering. Most of Asthagiri's work is done with mammalian cell cultures, where the ultimate goal is to do such things as coax a patient's own cells to cling to a surgically inserted man-made scaffolding and grow into functional tissues, such as blood vessels. Hence the interest in signaling networks—when they function properly, cells will spontaneously self-organize. (When they go awry, the cells run amok and turn cancerous. But that's another story.) Says Asthagiri, "If we could predict how multicellular structures form, we could design them from scratch, and perhaps one day grow entire organs." Of course, it's not that easy. As Sternberg says, "The bioengineers and synthetic biologists on campus like to say, 'To engineer is to understand,' but in practice, when you try to engineer, you immediately realize what you don't understand. And that drives further experiments, when you realize what's missing."

And in the study of human signaling networks, there's quite a lot missing. So Giurumescu decided to lower his sights and create a computer model of a model organism's model organ, for which he enlisted Sternberg's assistance. Says Sternberg, "Anand understands biology. Claudiu understands biology. I would just correct them if they were getting facts wrong. So there was a really seamless integration of the modeling and the understanding of the biology, versus having someone who's a modeler, and someone who's a biologist, and they're trying to figure out how to talk to each other." The worm literature is full of models, Sternberg adds, but, "Anand and Claudiu pulled out the critical parts of the circuit in a way that makes sense in terms of the molecular biology. It's a tradeoff between being simple enough to be able to analyze, but also capturing the interesting complexity, so it's a good model."

C. elegans goes through four larval stages over a period of about three days. Early in the third stage, the vulva starts forming from a string of six skin cells named P3.p through P8.p. (These are part of a group of cells called P1.p through P12.p, but the others play no part in this process.) P6.p, the central cell, chooses the so-called primary fate, in which its eight progeny form the channel leading to the uterus. P6.p's neighbors, cells P5.p and P7.p, select the "secondary fate," and their daughters form the vulva's lips—seven cells per lip, or 22 cells all told. The three outermost cells—P3.p, P4.p, and P8.p—opt for the "tertiary fate," in which their offspring fuse to the surrounding skin cells. A specific arrangement of cells is called a "phenotype," and nematode biologists use a shorthand that lists the fates numerically in ascending order. Thus the normal, or "wild type," pattern is called **3°3°2°1°2°3°**, meaning that cells P3.p and P4.p choose the tertiary fate, P5.p the secondary, and so on.

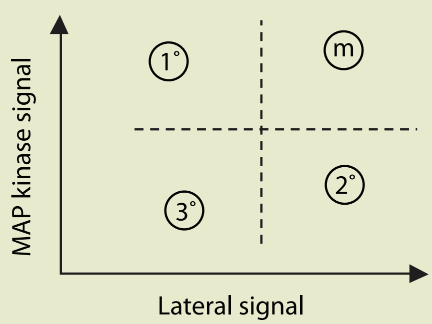
Two competing signaling systems determine what each cell does. One system, named the EGF pathway after its human equivalent, a substance called Epithelial Growth Factor, is based on a water-soluble protein. This protein is secreted into the intracellular fluid by a cell called the uterine anchor cell and diffuses away in all directions, so that its concentration falls off smoothly with the distance from the source. The anchor cell adjoins cell P6.p, which thus gets a huge dose of the EGF-like stuff, inducing it to pick the primary fate; cells that get little or no soluble signal default to the tertiary fate. The second system allows neighboring cells to talk to each other via interactions between two proteins called

THE EYE-CROSSING DETAILS



Every chemical interaction in this web of events has its own rate constant, $k_{whatever}$. The action begins when a molecule (the blue diamond) of the soluble signal, a protein called LIN-3, binds to its receptor, a protein called LET-23, on the surface of cell *i*. (To further confuse things with another layer of nomenclature, this is called an inductive signal, *I*, because it induces a change in the developing embryo.) The binding event triggers the conversion of a molecule named MAP kinase from an inactive form (mpk$_i$) to an active version (mpk$_i$*). This active MAP kinase in turn stimulates cell *i* to produce the Delta signaling protein, called LAG-2, which binds to the Notch receptor, LIN-12, on the surface of the adjoining cell, cell *i*+1, to send that cell a lateral signal (lat$_{i+1}$). This lateral signal proceeds to deactivate the MAP kinase in cell *i*+1, causing that cell to be less sensitive to the soluble inductive molecules (I_{i+1}) binding to its surface. This also causes cell *i*+1 to produce fewer Delta molecules of its own, meaning that it sends a weaker inhibitory signal back to cell *i*. Meanwhile, back in cell *i*, the activated MAP kinase molecules are causing the Notch receptors to get sucked back into the cell, deafening it. In addition to this crosstalk between cells, each cell also contains enzymes that steadily deactivate the MAP kinase, ensuring that a continual influx of the inductive signal is needed to keep things humming along.

The model encapsulates all this biochemistry to predict the internal state for each cell—that is, the level of active MAP kinase and the strength of the lateral signal that each cell will ultimately arrive at, given a specific set of initial conditions. "Now the challenge is to translate this biochemical state into a prediction about what the cell will actually do," says Asthagiri. "Will it become 1°, 2°, or 3°? We set up a simple mapping scheme based on the most conservative interpretation of the experiments. Maybe the dividing lines shouldn't be perpendicular, or even straight, but it's a way to start thinking about it." The map is divided into four quadrants:



A high MAP kinase signal and a low lateral signal cause the cell to choose the primary fate. A low MAP kinase signal and a high lateral signal lead to the secondary fate. And cells with a low MAP kinase signal and a low lateral signal default to the tertiary fate. The fourth quadrant, where the cell experiences a high level of both signals, is called the "mixed" outcome. While it has not been found in nature, it is a theoretical possibility that the model predicts will occur if specific tweaks are made to the biochemical circuit. Asthagiri and Sternberg plan to make these tweaks and see what happens. e&s

Adapted from Giurumescu et al., *PLoS Computational Biology*, Vol. 5, No. 4, e1000354, 2009.

Parameter	Meaning
I	Level of the soluble signal at the gradient's center
ΔI	Steepness of the soluble signal's gradient
χ	Strength of the lateral inhibition of the soluble signaling pathway
λ	Base level of the lateral signal
ϕ	Stimulation of lateral signaling to adjoining cells by the soluble signal
θ	Suppression of the lateral-signal receptors by the soluble signal
κ_M	Threshold of the soluble signal needed to stimulate the lateral signal
κ_L	Threshold of the lateral signal needed to inhibit the soluble signaling pathway

The model encapsulates all of the molecular interactions among all the various steps in the two competing signaling pathways in eight simple parameters.

Notch and Delta that sprout from the cells' surfaces. This lateral signal is responsible for triggering the secondary fate and, under normal conditions, ensures that only one cell chooses the primary fate by shutting down the EGF pathway in its neighbors. (For a closer look at the eye-crossing details of this process, see the opposite page.)

The EGF and Notch-Delta systems recur throughout the animal kingdom wherever tissues are forming. Their molecular mechanics have been exhaustively dissected, so Giurumescu was able to abstract how the two systems interacted. His model reduced the whole shooting match to eight parameters that allowed the concentrations of key molecules to be calculated within each cell as the vulva develops. He could then set each parameter—such things as the steepness of the soluble signal's gradient (ΔI), or the inhibition strength of the lateral signal (χ)—as he pleased, and watch how the cells responded.

Giurumescu began by seeing how well the model mimicked published laboratory studies. For example, one well-known mutant, the vulvaless 3°3°3°3°3°3° phenotype, is usually made by zapping the uterine anchor cell with a laser, destroying the EGF fountainhead. Would dialing down the soluble signal's peak level (I) in the model have the same effect? It did.

At the other extreme, the 2°1°2°1°2°1° phenotype—a nematode hedonist's dream with not one, not two, but *three* sets of naughty bits—is created by cranking up production of the soluble signal, which any of a number of mutations will do. The model reproduced this effect. It also predicted that preventing the gradient from tapering off—exposing all six cells to the same dose of the EGF-like molecule, whatever that dose might be—would give the same result. At the same time, researchers from the Howard Hughes Medical Institute discovered that another long-known mutation leading to the 2°1°2°1°2°1° phenotype actually *does* work by causing other nearby cells to join the uterine anchor cell in secreting the soluble signal, in effect flattening the gradient. (The seven-person team, headquartered at the University of Colorado at Boulder, included Min Han, a former Sternberg postdoc, as well as Sternberg and Byung Joon Hwang, then a Caltech postdoc.)

Says Asthagiri, "If our model can predict which specific interplay of signals leads to each known phenotype, it opens up a broader set of questions. Can we manipulate the network to discover what is evolutionarily possible? Like Darwin's finches, what types of diversity is the system capable of generating?" There are six cells in the nascent vulva, and four possible fates per cell: the primary, secondary, and tertiary ones found in the lab, plus one dubbed the "mixed" outcome that could occur if the two signals—EGF and Notch—were both cranked up. So in theory there are 4,096 (i.e., 4^6) possible phenotypes. "But are all of these outcomes accessible? Can you get everything under the sun, or does the network itself constrain what's possible?"

To find out, Giurumescu began dialing each of the eight parameters up and down in all possible combinations. In the lab, you might have a family of mutations that sets a protein's production to OFF, LOW, NORMAL, HIGH, and YIKES!, but the computer can specify very subtle differences in protein levels. Setting and verifying those protein levels experimentally would entail measuring them inside the cells of a living worm—a nearly impossible feat. Most importantly, the computer examines hordes of worms beyond the dreams of the most masochistic grad student, as the model encompasses some 214,000,000 possible mutations. Says Giurumescu, "It's like looking at 214,000,000 strains of worms at once. Each one is a data point."

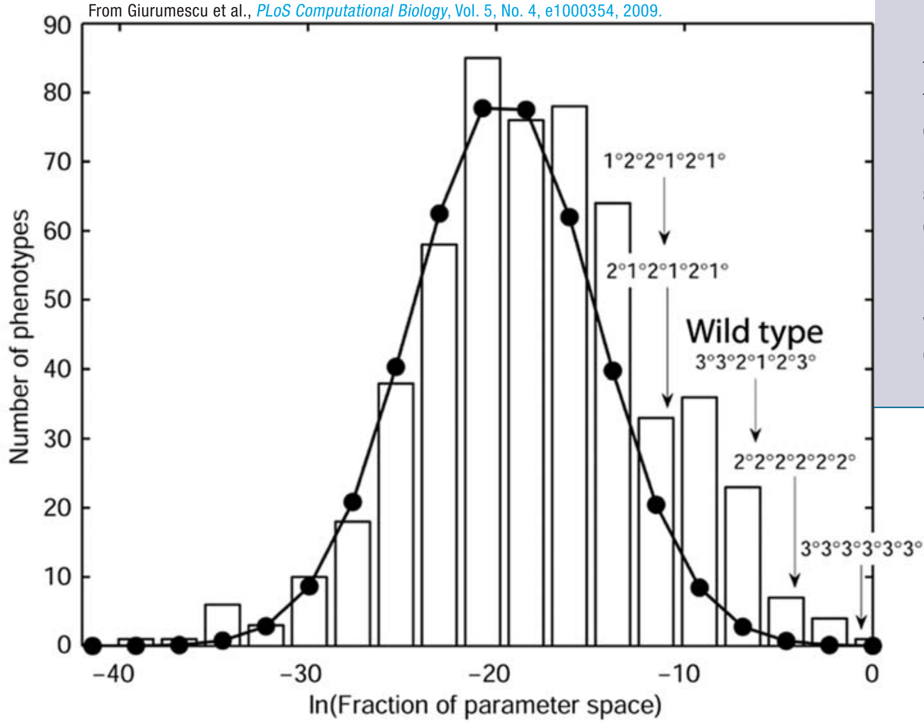
Giurumescu's final tally was some 560 phenotypes—only about 14 percent of the possibilities, but waaay more than the handful that have been bred in laboratories. Says Asthagiri, "This suggests that the way that connections are made within the network does constrain what's possible, but not to the level where the known phenotypes are the only possible outcomes. There's a lot more out there to explore."

WE'RE NOT IN KANSAS ANY MORE

It turns out that not all phenotypes are created equal. Giurumescu compiled an exhaustive map of the phenotypic landscape, an eight-dimensional cartographic nightmare in which he plotted the value of each parameter on its own axis and noted which phenotype occurred at that point in

In the lab, you might have a family of mutations that sets a protein's production to OFF, LOW, NORMAL, HIGH, and YIKES!, but the computer can specify very subtle differences in protein levels.

From Giurumescu et al., *PLoS Computational Biology*, Vol. 5, No. 4, e1000354, 2009.



In this plot of the number of phenotypes versus the size of the territory they occupy, the point labeled zero on the right end of the horizontal axis represents 100 percent of parameter space. Thus only the relative handful of phenotypes (not all of which have been labeled here) that lie under the right-hand tail of the curve are really viable, because they occupy significant amounts of parameter space.

8-D space. "Separating all the phenotypes and seeing how we could actually get from one to the next by doing single or double mutations took months," recalls Giurumescu. "I had two Pentiums running nonstop from January through March." Earlier, experiment-based phenotype maps were constructed on pretty sparse data. They tended to look like the state of Kansas, with each phenotype plotted as a city or town—a tiny dot on a vast prairie of empty space. People knew that each dot would have some size if you zoomed in on it enough, but nobody knew how big these municipalities really were.

Says Asthagiri, "We demonstrated that the wild type, and in fact all the phenotypes that have been described in the literature so far, are more like nations on a globe than cities on a map. They occupy widely varying amounts of real estate. We can move along some axis of the model, sometimes for a considerable distance, and still stay in the same phenotype. Then at some point we cross a border, and we wind up in another phenotype's territory. This has fundamental implications for how we think about species diversification. It suggests that the network itself doesn't have to change to produce new phenotypes; new signals and feedback loops don't have to be added or deleted. All you have to do is vary the connection strengths in the existing network sufficiently, and you will get new phenotypes."

Some phenotypes, like the wild type (3°3°2°1°2°3°), take up huge tracts of land, while most look more like Liechtenstein. Interestingly, the wild type is not nearly the biggest thing on the map. The vulvaless variant 3°3°3°3°3°3° sprawls through 54 percent of the 8-D volume—the equivalent, in terms of territory, of Asia, Africa, and Europe combined. Then comes the lipless 3°3°3°1°3°3°, which at 13 percent is slightly larger than Russia. This is followed by 12 other phenotypes, including five with at least one cell in the mixed outcome, before the wild type checks in at number 15. At a mere 0.2 percent, it occupies about as much real estate as Italy.

A certain amount of balkanization is a good thing. If the map were just one huge blob, then the species would have no capacity for change, because no matter how you jiggered the network's parameters, the phenotype would stay the same. This is a recipe for extinction. On the other hand, if the map looked like a Jackson Pollock painting, the species wouldn't be stable—the slightest jostling could push it into a new, and probably less fit, phenotype.

When Giurumescu plotted the size distribution of phenotypes on a logarithmic scale, he got a roughly bell-shaped curve. This means that the vast majority of phenotypes are mere postage stamps in parameter space, while the few in the right-hand tail (including the wild type) take up most of the room. This is the key to a species' stability, as Asthagiri explains. "You can poke and nudge the parameters quite a bit. You can make lots of small biochemical changes within the cells, or have them be in somewhat different environments, and still get a normal worm. The network doesn't have to be perfectly tuned to produce the wild-type pattern; instead, the worm has some wiggle room."

The phenotypes to the right of the wild type in the bell curve's tail are even more stable. "Once you arrive at one of them, you really have to flail around to get out," Asthagiri says. Since they're so big, they should be observable—any mutation you make has pretty good odds of pushing the worm into one of them. On the other hand, making one of the phenotypes found under the middle of the bell would be a very tricky proposition indeed. You'd have to overcome the natural biochemical variabilities that occur from cell to cell in a real worm, and the process of inducing a mutation is far from precise. And

Some phenotypes, like the wild type (3°3°2°1°2°3°), take up huge tracts of land, while most look more like Liechtenstein. Interestingly, the wild type is not nearly the biggest thing on the map.

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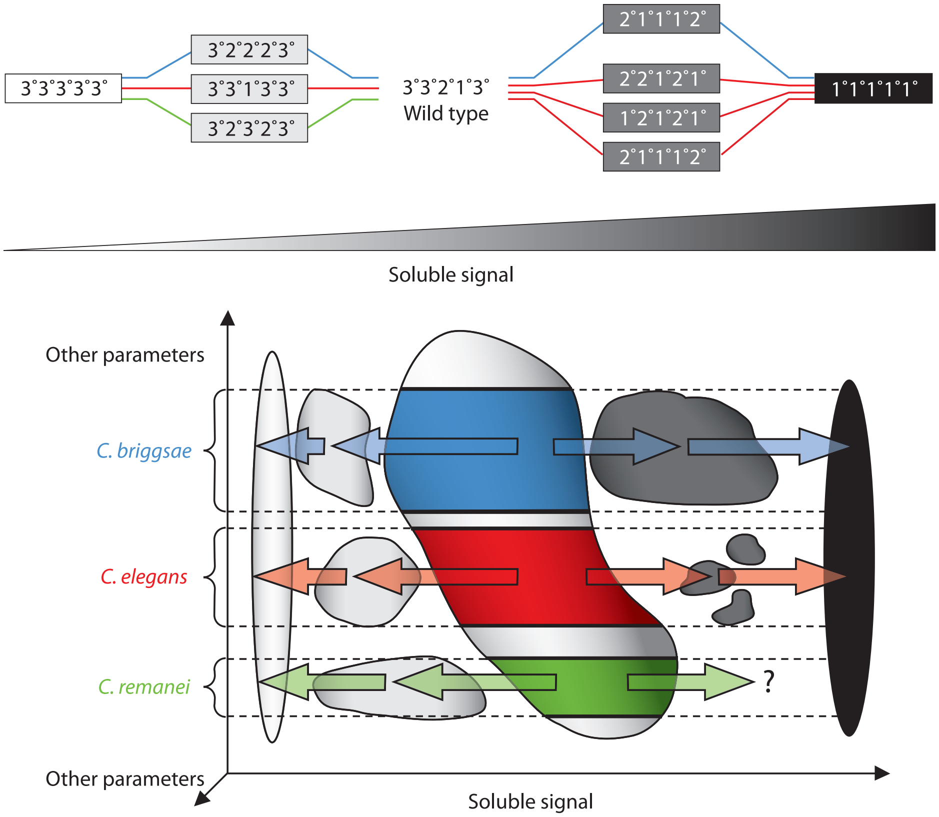

Top: Tweaking the network can cause big changes in the organism. Here, various settings for *I*, the level of the EGF-like signaling molecule, cause the three species (colored lines) to select different phenotypes at various points.
Bottom: That's because each species occupies a different region within the wild type's portion of the eight-dimensional parameter space. The wild-type region is relatively large, but the phenotypes adjoining it are not, so where you end up depends on where you begin.

indeed, all of the phenotypes that have been seen so far lie in that right-hand tail. The model predicts that there are 25 phenotypes that should be easy to get to experimentally, 15 of which have actually been made.

IN THE WILD TYPE THERE ARE MANY MANSIONS

But here's the kicker—not all of them occur in *C. elegans*. This little fellow is just the most famous member of its genus; two of its brethren, *C. briggsae* and *C. remanei*, are almost as beloved by worm biologists. In the wild, all three critters share the 3°3°2°1°2°3° phenotype. In the model, however, Giurumescu and Asthagiri discovered that each species occupies its own territory within the wild type's parameter space. Under the right conditions, giving each species the same push can thrust it into a different phenotype from its fellows. To return to cartography on yet another scale, the wild type might be Texas in a map of the United States. *C. briggsae* might live in the vicinity of Amarillo, where traveling some 250 miles east and a bit north would put the worm near Oklahoma City. *C. elegans* could be a denizen of the Dallas–Forth Worth area, and making the same phenotypic jump would land it in the vicinity of El Dorado, Arkansas. And finally, *C. remanei* might hang out at the Austin city limits, where that same journey east and north would end in the bayous somewhere south of Baton Rouge. The worms all set out from one state but ended up in three different ones, yet they all took the same trip—it all depends on the starting point.

This remarkable conclusion was sparked by results from a lab nine time zones east of Pasadena. While Giurumescu and Asthagiri were mutating model roundworms in a computer, Marie-Anne Félix, a former postdoc of Sternberg's, was embarking on a set of parallel experiments with real nematodes at the University of Paris. (She left Caltech just before Giurumescu arrived.) Félix studied the effect of the soluble-factor signal on *C. elegans* and 10 close relatives, but we'll just stick with the Big Three.

As expected, Félix found that low levels of the soluble signal caused all three species to assume the 3°3°3°3°3° phenotype. (Attentive readers will have noticed that there are now only five cells. That's because in *C. briggsae*, the P3.p cell does not participate in the process. From here on it's just P4.p through P8.p.) At normal concentrations, the wild type naturally resulted. But at an intermediate level that was less than normal, each worm produced a different phenotype—*C. elegans* made a lipless vulva (3°3°1°3°3°), *C. remanei* grew lips in the normal positions but did not form the central opening (3°2°3°2°3°), and *C. briggsae* created a third lip between the normal two (3°2°2°2°3°). When Félix cranked up the signal beyond normal levels, *C. elegans* and *C. briggsae* diverged again. *C. elegans* produced any of three outcomes: 2°2°1°2°1° and 1°2°1°2°1°, both of which had been seen in labs before, plus a new one, 2°2°1°2°2°. However, *C. briggsae* opted for another previously undiscovered phenotype, 2°1°1°1°2°. And finally, when doused in the EGF-like molecule, *C. elegans* and *C. briggsae* went all-primary (1°1°1°1°1°). At the same time, Giurumescu and Asthagiri discovered that the model assigned all of these outcomes reasonable amounts of space.

Which brings us back to the question of the origin of species. All these nematodes use the same network for the same end, so how do the various species wind up in different regions of the wild-type space? The connection strengths must be different—there's the same arrangement of levers and gears, if you will, but perhaps *C. remanei* has evolved a really stiff spring on one pivot. To confirm this, Giurumescu and Asthagiri plugged Félix's results into the model and worked backward, retracing the routes from the low-level mutants back into the wild-type space. It turns out that the *C. remanei* 3°2°3°2°3° phenotype requires a higher value for a parameter called ϕ than does the *C. elegans* 3°3°1°3°3° phenotype. This means that in *C. remanei*, the soluble signal produces a stronger lateral signal between adjoining cells than it does in the *C. elegans* on which the model was based. The model also gave *C. remanei* a lower threshold concentration (κ_M) at which the soluble signal turns on the lateral signal. But, says Asthagiri, "We can say anything we like about a bunch of Greek letters, but that isn't a testable prediction—we have to come up with a specific array of cells. And the true test for a modeler is, can you predict the result for an experiment that's never been done?" Félix had not tried the high-side experiment on *C. remanei*, providing the perfect opportunity.

In a striking display of economy, all of these forks in the evolutionary road can be produced without rewiring the underlying network of molecular signals.

Working forward from the *C. remanei* portion of the wild-type space and using the adjusted connection strengths, the model predicts that cranking up the soluble signal should lead, in ascending order, to 2°2°3°2°2°, 2°3°3°3°2°, and eventually 3°1°1°1°3°. Of these, only 3°1°1°1°3° has been seen before. (And, of course, at very high levels, our old friend 1°1°1°1°1° should eventually result.) Asthagiri and Félix met in July to plan a round of experiments that will provide the clincher. Stay tuned.

MAPPING TRAFFIC FLOW

When you alter the connection strengths, "the outcome may be the same, but the paths by which the network gets to the answer are different," says Sternberg. In other words, the various species all grow normal vulvas, despite their hidden diversity. As he explains it, "You might say that the best way to get to downtown L.A. is on Huntington Drive, and somebody else might say, 'No, it's the 110 Freeway.' In reality, the answer depends on the traffic. But let's say there's a parallel Pasadena where it's always better to go down Huntington, and a third one where it's always better to take the 110. Then people could do a really clear experiment—if we tried to drive down Huntington and found a big chasm, we'd realize, 'OK, we can't go this way.' But since the answer really depends on traffic patterns, we might get different answers because one person did the experiment at eight in the morning, and someone else did it at two in the afternoon. But everyone always ends up in the same place—there's an organ formed, and it happens perfectly. So Claudiu and Anand figured out all the possible routes and then learned about them by changing the parameters. Now they can say, 'Well, if the Dodgers are playing a home game, we can show that taking the 110 is not going to work.'"

Biologists can't look at every inch of pavement in the real process, so they have to guess which intersections have the critical stoplights that control the flow, and then figure out how to sample the appropriate molecules. Sometimes the researchers are just limited to whatever molecules are easy to detect—being at the mercy of wherever Caltrans put its traffic cameras, as it were. But in the model, all the dynamics are fully accessible. You can vary all of the connection strengths in the network in any combination all at the same time, the equivalent of driving all of the downtown-bound streets in the *Thomas Guide* simultaneously.

The collaboration's next step will be to apply the model to a closely related set of worm cells—the male sex organ, which is known as the hook. Some similar signaling molecules are involved in the hook's formation, but the structure that emerges is very different. Evolutionary studies have found that the hook and the vulva probably diverged at least half a billion years ago. Can the model predict how that might have come about?

Giurumescu is now a postdoc in a worm lab at UC San Diego, but Sternberg, his grad student Paul Minor, and Asthagiri are building a model of another signaling pathway called WNT. Not all of the players in the WNT pathway have been identified, so Minor's first job is to work out the relationships between the various parts. Says Sternberg, "The Notch-Delta, WNT, and EGF systems are three of the big food groups of signaling pathways, and they all work together both in the vulva and the hook. But beyond that, they're in every organ. They're involved in all different tissues in worms, flies, and mammals. The way they're coupled might be different, and that's another reason to look at the general case—what are the general ways you can couple these pathways and tweak them? They can be working cooperatively, or antagonistically, or in parallel. Or they may be unrelated. But they're going to be used in all those ways somewhere."

So, 150 years after the publication of *On the Origin of Species*, it appears that, at least in the genus *Caenorhabditis*, the wild-type space contains the jumping-off point for many phenotypes. Different species live in different parts of that space, so each may have ready access to a different set of phenotypes; thus the worms might, over time, evolve modified body parts to exploit various niches in their environment. But in a striking display of economy, all of these forks in the evolutionary road can be produced without rewiring the underlying network of molecular signals—simply altering the connection strengths, a much easier feat in evolutionary terms, will suffice. And if it works that way in the 959 cells of the nematode, it probably works that way in fruit flies, finches, and us. e&s

PICTURE CREDITS
27 — Bob Paz, Yingchuan Qi; 28 — Erik Jorgensen; 29, 30, 33 — Doug Cummings

Anand Asthagiri earned his BS in chemical engineering from Cornell in 1995, and a PhD from MIT in chemical engineering with a minor in molecular cell biology in 2000. He then was a postdoc in the Department of Cell Biology at Harvard Medical School before coming to Caltech in 2002.

Paul Sternberg got in on the ground floor of the nematode business, getting his PhD in biology at MIT in 1984 under the supervision of H. Robert Horvitz, who shared the Nobel Prize in Physiology or Medicine in 2002 for his studies of programmed cell death in* C. elegans. *Sternberg came to Caltech in 1987 and has been the lead principal investigator for WormBase, the online compendium of nematode gene and protein data, since 1999.

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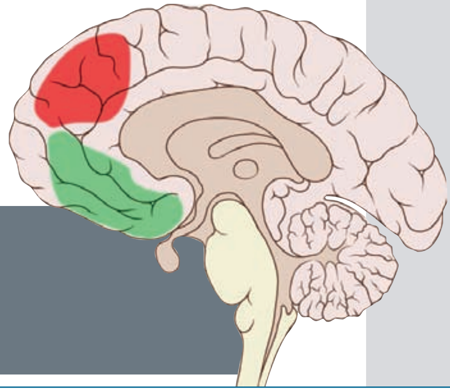
The Neural Basis for Self-Control

You're on a diet, but you really want a piece of that chocolate cake. What's going on in your brain as you struggle to resist temptation?

***Antonio Rangel** is an associate professor of economics. After graduating from Caltech with his BS in economics in 1993, he received his PhD from Harvard in 1997. He then became an assistant professor of economics at Stanford before returning to Caltech in 2006. He is the president of the Society for Neuroeconomics. The following, based on his talk at the 72nd Seminar Day in May 2009, was funded by the **Moore Foundation** and the **Economic Research Service** of the U.S. Department of Agriculture on Behavioral Health Economics Research on Dietary Choice and Obesity. This article was edited by Marcus Y. Woo.*

Many of the world's problems are the result of faulty decision making. If we could understand how the brain makes decisions, then maybe we could make better choices. I'm a professor of economics and part of a team of psychologists and neuroscientists



Researchers are finding that the ventromedial prefrontal cortex, or vmPFC, (green) is where the brain encodes how much you're inclined to make a particular choice. The dorsolateral prefrontal cortex, or DLPFC, (red) has to come online for the brain to exercise self-control.

By Antonio Rangel

at Caltech tackling the problem of how the brain makes decisions. In particular, I'm interested in self-control, which is at the core of many of the most pertinent public-policy and health issues in the United States. Think about addiction. Think about obesity, which is a very personal problem for me—I like sweets a little bit too much. Or think about the low savings rates of the United States.

All of these problems are the result of poor decision making, and have inspired us to ask three questions. First, why does the brain have a problem with self-control at all? Why has evolution developed a machine that becomes conflicted while trying to make good decisions—one of its most important tasks? Your visual system, for example, doesn't give you conflicting outputs. If I look at you, I see a clear, sharp image. Why doesn't your decision-making circuitry act like that? The second question is, how does the brain actually exercise self-control? The final question is the most important one: what is different between the brains of people who can and cannot exercise self-control? Can we make the second group more like the first?

We have been doing a lot of experiments to see what's going on in the brain while it's trying to exercise restraint. We primarily study the self-control involved in dieting. We're interested in obesity, and, more importantly, dieting, which is a simple paradigm that allows us to control a lot of variables.

Over the last two years, we've discovered that two important mechanisms in the brain kick in when we make decisions—such as choosing to eat an apple instead of a piece of cake. The first involves an area of the brain just a little above and behind the eyebrows called the ventromedial prefrontal cortex (vmPFC). When you are presented with a choice of objects—say a cookie or a piece of fruit—this region encodes a value for each object in the firing rates of neurons. The more frequently the neurons fire, the higher the value, and the more likely you'll end up choosing that object. It seems that this value signal determines your choice—regardless of whether you are inherently good at self-control.

The second mechanism we discovered determines the difference between a good and a bad self-controller. In people who have trouble with willpower, the signal seems to reflect only the immediate and effective value of things. When they see a cookie and a piece of fruit, they think, "Cookie: great taste. Health: who cares?" Health doesn't get incorporated into the value signal. A good self-controller, in contrast, also activates another area of the brain called the dorsolateral prefrontal cortex (DLPFC). This region modulates the values generated by the vmPFC so that they include long-term considerations, like keeping your weight down, guiding you to make more sensible choices. The difference between a good and a bad self-controller is not that the bad one likes cookies more. It's that this other area of the brain—the DLPFC—does not come online to effectively modulate activity in the vmPFC.

DECISIONS, DECISIONS . . .

We started with a very simple—yet useful—conceptual framework. Suppose you have to choose between several items. What does the brain need to compute? The brain has to first identify the items and then assign a value to each one. The brain then compares those values to make a choice. But, of course, you're not sitting there saying, "Hmm, the value of the cookie is five, the apple is a three. Therefore, I should go for the cookie." This process happens in as little as 300 milliseconds and can be totally unconscious.

In an experiment, we asked 19 test subjects to decide how much certain kinds of food are worth to them. While they made these decisions, we examined their brains with a functional magnetic resonance imaging (fMRI) machine, which helps map brain activity. The device is similar to the MRI scanner that you may have been in, unfortunately, to examine a torn ACL. Active areas of the brain consume more oxygen, and it turns out that the amount of oxygenated blood that comes into an area of the brain is proportional to neural activity there. Oxygenated blood and deoxygenated blood have different magnetic properties. The fMRI machine creates a three-tesla static magnetic field—a very, very strong and very stable magnetic field that allows us to detect tiny, localized changes in the brain's magnetic field and see where the value decisions are encoded. While the subject lay in the scanner, a screen displayed pictures of different snacks—junk food, like candy bars and

Listen to a podcast of Rangel discussing his research on the brain and decision making.

The difference between the self-controllers and non-self-controllers were striking. What was going on in their brains that was setting them apart?

chips—for four seconds. We had given the subjects money to buy these items, and they had to type in a bid of $0, $1, $2, or $3.

These weren't just hypothetical situations. The decisions were real. Before coming to the lab, the subjects were told to fast for four hours, and that they would have to stay in the lab for half an hour after the experiment. They were hungry, and the only thing they could eat was whatever they had bought from us. So that they didn't have to worry about budgeting their money, only one of their transactions—one we randomly selected—was implemented.

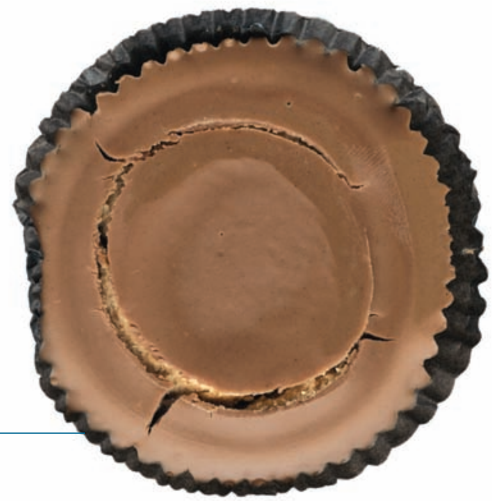
If I were a vision neuroscientist instead of a behavioral neuroscientist, the experiment would be very simple. I would show you a stimulus and vary an objective, easily quantifiable characteristic, such as color or contrast. Then I would see if there's an area of the brain where the activity is changing at a rate proportional to the change in that characteristic. But the difficulty in behavioral neuroscience is that it deals in subjective, hard-to-measure values. I need to use a trick—and this is where experimental economics meets neuroscience. In our experiment, we didn't sell the food at the price the subject offered, but used a method called a Becker-DeGroot-Marschak auction. In this procedure, you tell me that something is worth X dollars to you. I pick a random number, and if that number is less than or equal to X, you get the item and you pay the number that was chosen randomly. But if the random number was bigger than your bid, you keep your money and don't get anything. If you think about it, you can see that the optimal strategy is to bid the true value of the item—not a penny more, not a penny less—which allows us to get an objective measure.

We can measure changes every two seconds in brain activity within regions as small as a cube one to three millimeters per side. Even in such a small box, called a voxel, there are hundreds of thousands of neurons. But, as you'll see, these measurements are still very useful. We want to know if any of those boxes show a statistically significant response—above or below the normal background activity level—that's proportional to the value of the item. If so, then we can conclude that those voxels are probably involved in computing the value signal. We found that activity in the vmPFC correlates with that value.

We also ran an experiment in which the subjects had to choose between things they didn't like, such as canned vegetables and baby food. The experiment was the same as the one I described above, except that now the subjects had to pay *not* to eat the food. The bidding rules were the same, but now we're measuring how repellant something is, rather than how appetizing. At the end, we randomly chose one of the trials to implement, and unless the subjects won the auction, they had to eat the food, which wasn't the tastiest of treats. At one point we had pig's feet, but it was just too much for American students to swallow.

We asked a similar question with this experiment: were there any areas of the brain that encoded how disliked something was? In other words, did neuron firing rates increase proportionally with aversion? The answer, we found, was no—not even if you squint at the data. However, we found that there are areas of the brain in which activity *decreases* proportionally to how aversive something is. Furthermore, the relevant regions were the same as those of the previous experiment. If you put the brain scans from both experiments on top of each other—remember, each experiment had different foods, and was conducted on different days—the active areas overlap, suggesting that this region can encode a positive or negative value signal. For the appetizing case, the brain ramps up activity; in

Left: How much would you pay *not* to eat baby food (carrots, in this picture)? Top right: Do you have the self-control to resist a chocolate peanut-butter cup?



the aversive case, it ramps down activity.

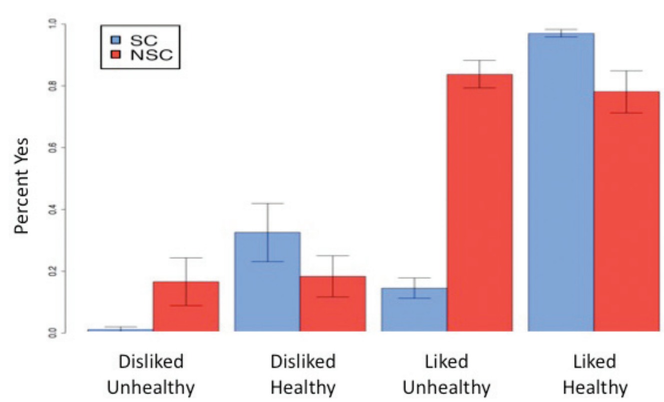
But, you might say, maybe food is a special case—what about other things? So we did another version of the experiment in which we asked people to bid for an 80 percent chance to get food, Caltech paraphernalia, and cash. For example, subjects were asked how much they'd be willing to bid for an 80 percent chance at receiving $3 or a Caltech hat. This experiment showed that the items' values were all encoded in the same brain region, regardless of what type of item they were. There are also numerous other, more technical experiments that identify the vmPFC as the place where the brain encodes value. For example, Camillo Padoa-Schioppa and John Assad at Harvard measured the electrical activity in single neurons in the vmPFC of monkeys while the animals made choices between different types of juice. The researchers found that activity in these neurons encoded value signals, which is consistent with our findings.

AN OFFER YOU CAN'T REFUSE?

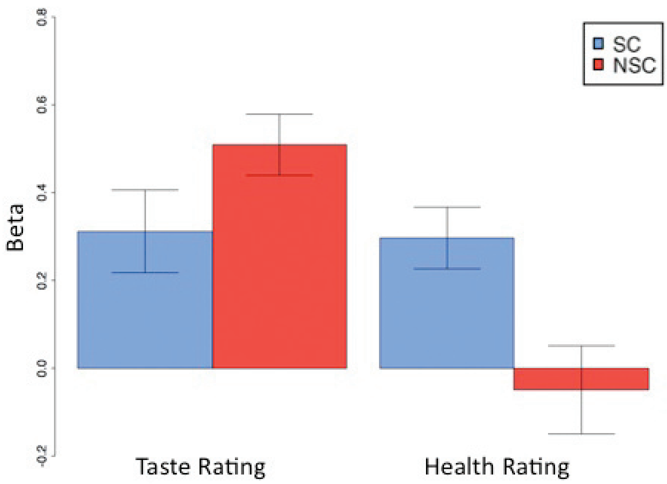
This brings us to the DLPFC, which needs to come online for the brain to consider the long-term benefits of a particular choice. To study this, postdoc Todd Hare, Kirby Professor of Behavioral Economics Colin Camerer, and I recruited dieters and nondieters by offering them $100. As before, the subjects were asked to fast so that they would be hungry when they came to the lab. We then asked them to make several food choices while in the scanner. The stimuli in this experiment were healthy items, like fruits, and unhealthy ones, like candy. Every subject had to give each item a health rating, independent of taste, on an integer scale of -2 to 2. Then they were asked to rate everything on taste, independent of any health considerations, on the same scale. We could then select a health- and taste-neutral item for each person, and once we had those reference items, we asked the subject to choose between a new food item and the neutral item, which remained constant with each trial. This way, we knew that it was the new item that drove whatever signals we detected. At the end of the experiment, we again randomly implemented one of their decisions, and they had to eat whatever they had chosen.

Based on the data, we then divided the subjects into self-controllers and non-self-controllers. Certain trials required self-control—if I were to show you an item that is tasty but unhealthy, you should say "no." But if I were to show you something that is tasty *and* healthy, you don't need to exercise any self-control. We categorized someone as a self-controller if he or she exercised discipline in at least half of the trials that required it. A typical self-controller is more likely to choose the healthier item; they're not really responsive to taste. But a non-self-controller—that's me—cares only about taste.

When no self-control was required, both groups behaved the same way. People always chose healthy things that they liked. In contrast, we could not get people to go for food that was disliked and healthy; no one was clamoring for broccoli. Still, the differences between the self-controllers and non-self-controllers were striking. What was going on in their brains that was setting them apart?



Percentage of self-controllers (blue) and non-self-controllers (red) who chose different combinations of healthy and liked food items. Those who were good at self-control were more likely to choose the healthier option, regardless of how much they liked it. This and the next two plots are from *Science*, Vol. 324, pp. 646-648, May 1, 2009. Reprinted with permission from AAAS.



In self-controllers (blue), both the taste and health ratings of food influenced the activity of the vmPFC, as measured by the parameter beta. For non-self-controllers, only taste was important.

THE SELF-CONTROLLING BRAIN

We looked at whether taste or health ratings drove the value signals in the vmPFC for the two groups. In self-controllers, both health and taste ratings influenced vmPFC activity. In non-self-controllers, the vmPFC was only affected by taste. There was a large correlation between how much the subjects' health ratings affected their decision and how much the ratings affected vmPFC activity.

When the brain exercised self-control, the DLPFC was more active among self-controllers than non-self-controllers. Furthermore, the DLPFC is active whenever the brain successfully practices self-discipline, regardless of whether you're good at self-control. These results by themselves don't prove the powerful idea that the DLPFC modulates the vmPFC to drive choices. However, we then found more evidence supporting this idea.

Sitting a bit farther down the prefrontal cortex, behind the face, is a region called the IFG/BA46. This area appears to be an intermediary between the DLPFC and the vmPFC. For non-self-controllers, the DLPFC doesn't come online to modulate the vmPFC. But when a self-controller is confronted with, say, a piece of chocolate cake, the DLPFC comes online and inhibits the IFG/BA46. Lower activity in this intermediate region then lowers the activity of the vmPFC, and the subject declines the cake. So all of the pieces fit together just right.

The data suggests that a lack of self-control is the result of deficient DLPFC function. This is interesting for a couple of reasons. The DLPFC is involved in a host of other behaviors, such as emotional regulation—calming yourself down when something upsets you. This brain region also plays a role in cognitive control, which enables you to override certain ingrained responses. For instance, you might be accustomed to reaching for the light switch on the right when you enter your living room. But you don't want to reach to the right every time you enter a room. Furthermore, it's been shown that high IQ and behavioral self-control are highly correlated, and the DLPFC seems to be very important when people solve puzzles involved in IQ tests. Thus, we need to explore whether this region is involved in a series of regulatory mechanisms that are necessary for good emotional regulation, cognitive control, self-control, and cognition in general—that is, to be able to retrieve and use information.

Why is it that I can stay up until 3:00 in the morning working like an animal—I mean, I love my work, but it does require some self-control—but I just cannot say no to Pie 'n Burger [a popular local eatery that specializes in, well, pies and burgers]? We don't know, and the reason we don't know is that there is something deeper behind this. Self-control occurs when the DLPFC comes online and modulates the vmPFC, but what makes the DLPFC come online in the first place? And does it only come online in specific circumstances? Hopefully, we'll soon be able to answer those questions, and, within one or two decades, we may be able to stimulate the DLPFC directly to make sure that it gets deployed during important decision-making situations. e&s

PICTURE CREDITS

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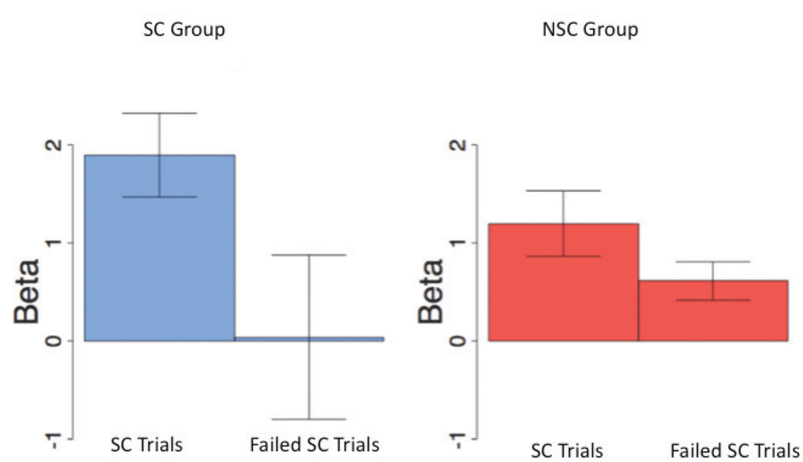

Both self-controllers (blue) and non-self-controllers (red) showed more activity in the DLPFC when they were successful at practicing self-discipline.

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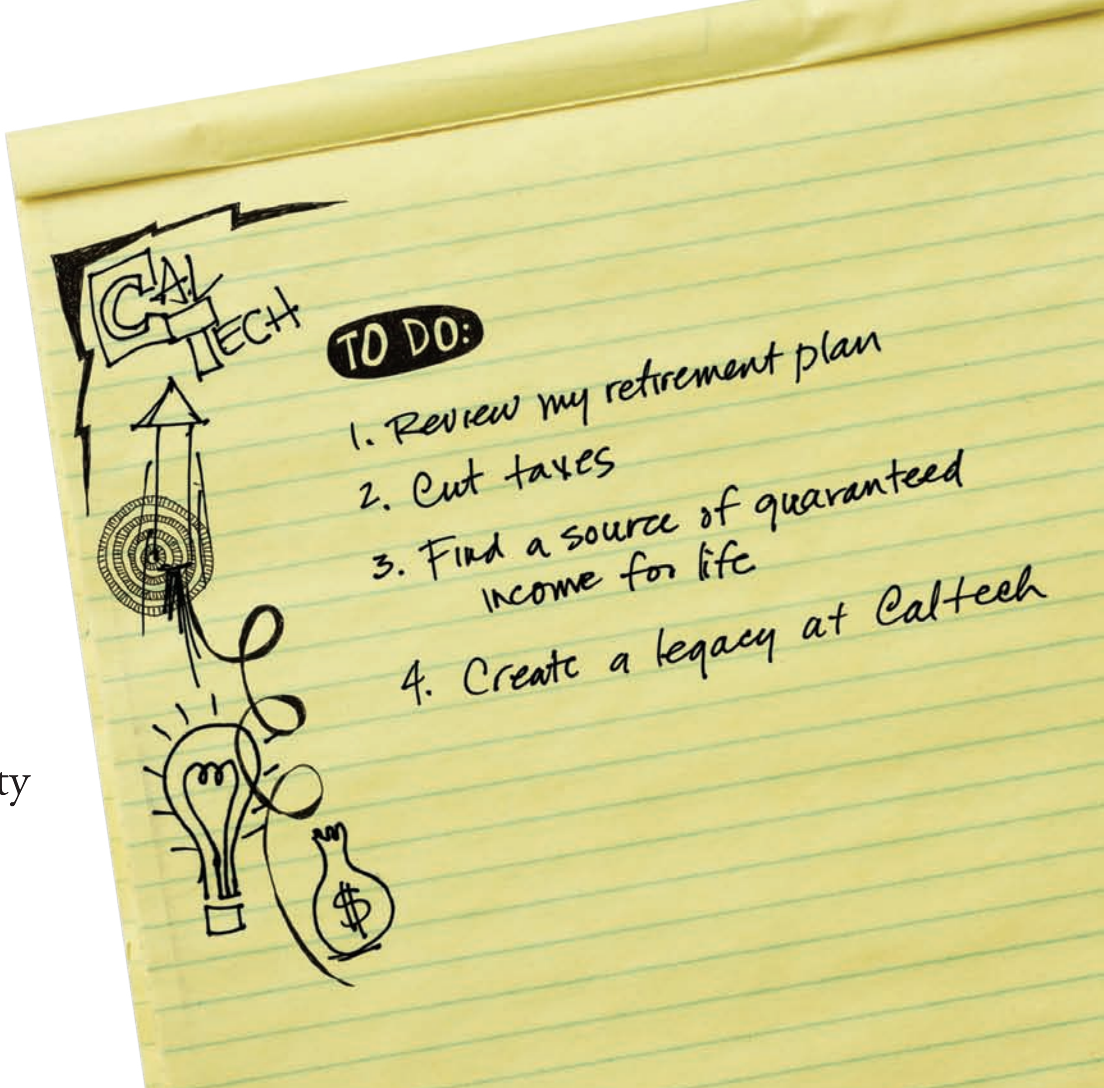

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LETTERS

About *E&S* being online-only:

▪ ▪ ▪

A year ago I would've said "no way, I wouldn't read *E&S* online!" But in February Dell had a sale and I got a Mini 9 netbook for $225. Now I read the *Boston Globe*, the *WSJ*, the *NYT*, the *Economist*, *Education Week*, and lots of other stuff on my little netbook. So I say "Go For It!" . . .

Online will open you up to audio and video components to articles, dynamic links, and reader forums. So I think on balance it is a good thing (and be assured I am a late adopter who lives in a house groaning under the weight of bookshelves lining every available wall).

Joshua Roth [MS '91, PhD '94]

▪ ▪ ▪

I do have a Kindle, and have been surprised at how much I enjoy reading novels on it. But magazines are different; the larger format and extensive full-color pages cannot be duplicated on a Kindle-type device yet.

Ole Eichhorn [BS '79]

▪ ▪ ▪

I for one am all for going digital-only, and really making it a full-featured, interactive Web publication. What I would *really* like to see is a relatively open Caltech blogging forum . . . bringing together all the different content streams that Caltech produces. Infrequent but in-depth features like we have in *E&S*, student news and concerns like we have gotten from the *Tech* and the GSC newsletter, and more frequent blog-like commentary from researchers all over campus . . . all of this with relatively open participation from the Caltech community, and commentary allowed from the public.

Zane A. Selvans [BS '98]

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I completely understand the position you find yourself in. However, when *E&S* stops printing, it will become yet another of those periodicals that shows up in my in-box and I click Delete. When I go through my e-mail is simply not when I wish to read a magazine. Regarding the 500-year-old technology of printing, drinking water from a cup is a good deal older technology, and I have no plans to abandon that practice any time soon.

Bob Burket [BS '65]

▪ ▪ ▪

Here's how I make use of online and print magazines (I subscribe to several that offer both, e.g., *Newsweek*, *New Scientist*, and others):

Web: online lookup of an occasional headline or past article;

Print: everything else. . . .

I've never had the battery die on a print magazine; I've never been required to pay $15 at an airport to connect my eyes to the words on the screen for a magazine I already own. Can't quite say the same about a Web mag. . . . The value of *E&S* to me is everywhere and everywhen BUT when I'm connected to the Internet.

Robert J. Lang [BS '82, PhD '86]

▪ ▪ ▪

Having the content available on a website will be extremely useful, and creating a presence on sites like Facebook or whatever comes next in social networking makes it easier to share the great articles with people outside the Caltech community.

Bill Craven [BS '87]

▪ ▪ ▪

I can read a good article in the time it takes my computer to boot up, and I don't have more than a few moments here and there.

Rich Alvidrez [JPL]

▪ ▪ ▪

Reading *E&S* on my computer screen would be like eating Christmas dinner on paper plates while standing. The quality is there, but it's just not the same. I already spend too much time looking at my monitor. I want my quality reading to be hand-held so I can savor it where and when I want.

Walter Goeddel [MS '51]

▪ ▪ ▪

I have recently been catching up on back issues as my son has gotten older and I will miss reading it at the table while he gets around to eating. And that is the problem. Until there is a technology which I can take anywhere and spill things on with impunity, I am very unlikely to read any publication online.

Jen Trotter [BS '95]

▪ ▪ ▪

If I want to take a copy of *E&S* with me to the pool or the beach, it's ready to go. If I get a little sand in the magazine at the beach, no problem. If I drop the magazine, it still works.

I bring the magazine home with me and leave it out. My wife likes reading it. My son (who is not close to being college age) loves skimming through it. If I leave it out at work, people invariably pick it up, flip through it, and often ask to borrow it for a while.

Related to this is another problem with getting rid of the hard-copy version of *E&S:* the foreclosure of the "happy accident," the experience of stumbling across a fantastic new article on a cool subject that you knew nothing about. . . . This quality of surprise and delight—embodied by the ability to find a copy of *E&S* all over campus—is what makes being on campus at Caltech an inspiring place.

Bob Gutzman [Caltech neighbor]

OBITUARY

HANS W. LIEPMANN

1914–2009

Hans Wolfgang Liepmann, a pioneering researcher and passionate educator in fluid mechanics, passed away on June 24 at his home in La Cañada Flintridge. He was 94.

Liepmann, the Theodore von Kármán Professor of Aeronautics, Emeritus, came to Caltech in 1939 and was the third director of Caltech's Graduate Aeronautical Laboratories (GALCIT), from 1972 to 1985.

Known for his sharp wit and distinctive accent, Liepmann was a noted teacher who mentored more than 60 PhD students and hundreds of undergraduates during his career at GALCIT.

He was born in Berlin in 1914. His father, a well-known physician and hospital director, decided to emigrate following the rise of the Nazi government and the infamous Reichstag fire in 1933. Liepmann joined his family in Turkey in 1934 after his father was invited to be head of the gynecology department at the University of Istanbul. He later studied in the physics department at the University of Zürich, and pursued his doctoral studies on low-temperature physics under Richard Bar.

Liepmann came to the U.S. in 1939 after impulsively expressing an interest in "hydrodynamics" during a drinking party at his PhD defense. An offer from Theodore von Kármán led to a research position in experimental fluid mechanics at GALCIT, where Kármán was the first director. Liepmann studied boundary layer instability, transition to turbulence, and various turbulent flows. With the entry of the U.S. into World War II, he began research on problems associated with high-speed flight, including transonic flight phenomena and interaction of shock waves with boundary layers on aerodynamic surfaces.

By 1949 he had advanced to professor of aeronautics at Caltech and had developed a vigorous program of research. A strong believer in the importance of teaching, he was instrumental in Caltech's introduction of the applied mathematics option in 1967 and the applied physics option in 1974. Throughout his career, up to retirement, Liepmann was devoted to teaching both graduate and undergraduate courses. The enthusiasm, clarity, and teaching effectiveness of his lectures are legendary.

Liepmann was elected a member of the National Academy of Engineering and the National Academy of Sciences. He was a recipient of the National Medal of Technology and the Ludwig Prandtl Ring—the highest honor conferred by the German Society for Aeronautics and Astronautics. In 1986, President Ronald Reagan awarded him the National Medal of Science.

Liepmann leaves behind sons Dorian, Till, Christopher, and Paul, and two grandchildren. His wife, Dietlind, passed away in 1990.

A memorial service for Liepmann is scheduled for January 23, at 2:00 p.m. at the Athenaeum. *—JW* e&s

FACULTY FILE

NEW MOSH . . .

Geoffrey Blake (PhD '86), professor of cosmochemistry and planetary sciences and professor of chemistry, became the new Master of Student Houses (MOSH) on July 1. Blake, a faculty member since 1987, has had considerable experience working with undergraduates. He is starting his fourth and final year as the chair of the Freshman Admissions Committee, and was one of the original Faculty-in-Residence at Avery house. His stint as MOSH will last five years. e&s

. . . AND NEW SEISMO-LAB DIRECTOR

Michael Gurnis, the Smits Professor of Geophysics, has been appointed the new director for the Seismological Laboratory, taking over for the lab's acting director, Robert Clayton, professor of geophysics. e&s

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