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Engineering & Science

IN THIS ISSUE:

A Global Challenge ▪ A Financial Crisis ▪ A Natural Disaster ▪ A Mission to Mars

VOLUME LXXI, NUMBER 4, WINTER 2008

California Institute of Technology

ON THE COVER

This artist's rendition shows a revamped Union Station in downtown Los Angeles as one hub of a proposed "bullet train" system that will provide high-speed, emissions-free transportation between California's major metropolitan areas. Such a system will be an essential part of our efforts to combat global warming and end our dependence on foreign oil, says JPL's chief technologist. For the rest of the story, see page 12.

LETTER FROM THE EDITOR

Interesting times, indeed.

In case you can't decide which form of impending doom you'd prefer to worry about, this issue takes a look at two ongoing man-made disasters and one potential natural one. But as Paul Dimotakis says in his article on climate change, "One cannot announce that the sky is falling without offering a vision for how to get out from under it." Every crisis contains an opportunity, and some people at Caltech and JPL are thinking very hard about opportunities for positive change in the way we do things. We may be able to avert the worst effects of global warming. We can design our financial system to be more impervious to the shocks that will inevitably occur. And we're learning how to live in earthquake country.

In the meantime, life goes on. A steady diet of calamity is unhealthy, and researchers here live in the future. They are working on really cool things that will benefit us in the long run, regardless of our immediate (or future) travails. Thus we also bring you the story of the Mars Phoenix, a spacecraft that did itself arise from the ashes to triumphantly land on the frozen northern plains of Mars and give us our first taste of Mars's frozen water.

As the counterculturists used to say, "Onward, through the fog!"

– DOUGLAS L. SMITH

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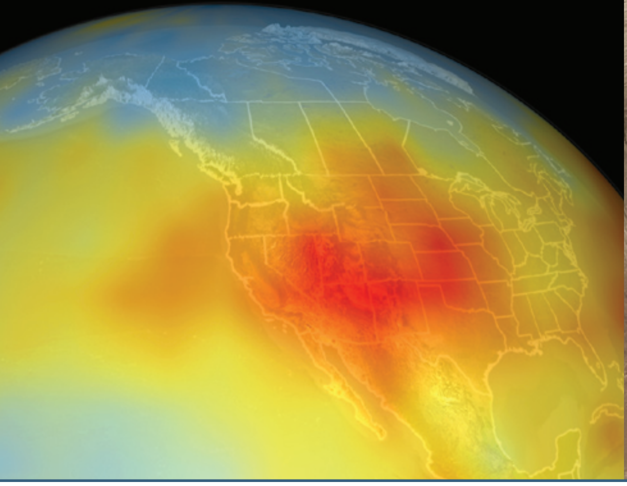


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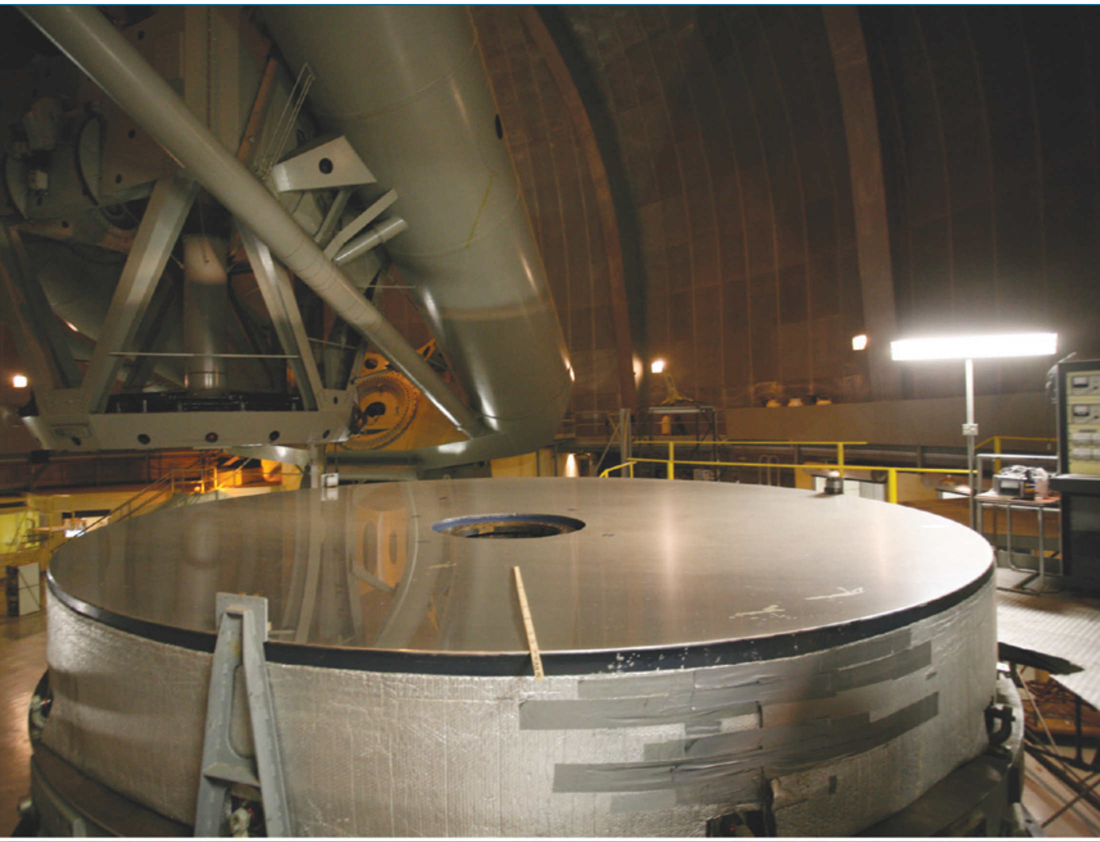


THE SHINING

There's a fresh gleam in the eye of the Hale telescope. In November, the 200-inch mirror at the Palomar Observatory was treated with a good scrub and a shiny new coat of aluminum.

After staring into space for nearly 300 days out of the year, the mirror accumulates dirt and dust that even weekly cleanings can't get rid of. So, every year or two, the mirror is unmounted, washed, and given a new reflective surface.

First, the staff uses a cart to lower the 14.5-ton piece of glass from the scope. They then clean the mirror with soap and water, keeping the surface wet at all times to prevent spots. Next, an acid wash called "Green River" strips away the old aluminum. After some more cleaning, drying (with paper towels), and inspection, the mirror's ready for its new shine.

A 17.5-ton bell jar is lowered over the mirror. It takes a day to suck out enough air to make the vacuum the mirror needs to be recoated. Inside the chamber, hundreds of tungsten coils covered in aluminum are heated to more than 500° C. The heat vaporizes the metal, and the aluminum deposits onto the mirror, forming a layer less than eight millionths of a centimeter thick.—*MW* E&S

After a spa treatment and a fresh coat of aluminum, the Hale telescope's 200-inch mirror boasts a new shine. The butt end of the telescope, from whence the mirror came, looms in the background of the "before" picture (top).

GET YOUR BLOOD SCANNED ON A BARCODE CHIP

Some day when you put a pinprick's worth of blood into a lab-on-a-chip developed at Caltech, you'll be able to tell within 10 minutes if you're at risk for heart disease or cancer. The device, known as the Integrated Blood-Barcode Chip, or IBBC, measures the concentrations of dozens of proteins in your blood serum at once. It was developed by a group led by James Heath, Caltech's Gilloon Professor and professor of chemistry, along with postdoc Rong Fan and grad student Ophir Vermesh, and by Leroy Hood (BS '60, PhD '68), president of the Institute for Systems Biology in Seattle, Washington.

An IBBC is essentially a microscope slide coated with silicone rubber. The rubber's underside is molded into a system of microscopic channels. As a pinprick of blood flows through the channels, the protein-rich plasma is separated out, and protein biomarkers are measured in the plasma.

Nowadays, blood tests take hours, not counting the time needed to draw a vial of blood from your arm and deliver it to the lab. There, the blood is centrifuged to separate the plasma, which is analyzed for each specific protein separately. "The process is labor intensive, and even if the person doing the testing hurries, the tests will still take a few hours to complete," says Heath. "We wanted to lower the cost of such measurements by orders of magnitude. We measure many proteins for the cost of one. Furthermore, if you reduce the time it takes for the test, the test is cheaper, since time is money." A test kit for a single protein currently costs about $50. Says Heath, "We are optimistic that our platform, when fully developed, will reduce this cost to pennies per biomarker."

A single chip can simultaneously test the blood from eight patients, and each test measures many proteins at once. "We're aiming to measure 100 proteins per fingerprick within a year or so. It's a pretty enabling technology," Heath says.

The IBBC analyzes a blood drop by gently pumping it through a relatively wide channel. Smaller channels branching from the main one skim off some of the plasma and direct it along a "barcode"—one per channel. Each line in the barcode is 20 millionths of a meter wide and covered with an antibody that allows it to capture a specific protein from the plasma passing over. When the barcode is "developed," the individual bars emit a red fluorescent glow, whose brightness depends upon the amount of each protein captured.

In the paper announcing this work in the December issue of *Nature Biotechnology*, the researchers measured human chorionic gonadotropin, a hormone produced during pregnancy. "The concentration of this protein increases by about 100,000-fold as a woman goes through the pregnancy cycle, and we wanted to show that we could capture that whole concentration range through a single test," Heath says. The scientists also analyzed the blood of breast- and prostate-cancer patients for a number of biomarkers. These proteins vary in type and concentration—a woman with breast cancer, for example, will produce a different suite of biomarkers than a man with prostate cancer, and a woman with an aggressive breast cancer may produce proteins that are different from a woman with a less-deadly cancer. After the diagnosis, biomarkers may change as treatment progresses, so an IBBC could also be used much as a diabetic tests his or her blood sugar.

The barcode chip is now in human clinical trials on patients with

A test kit for a single protein currently costs about $50. Says Heath, "We are optimistic that our platform, when fully developed, will reduce this cost to pennies per biomarker."

glioblastoma, a common, aggressive brain tumor. The researchers are also using the chips to determine how diet and exercise change the composition of the proteins in the blood of healthy people.

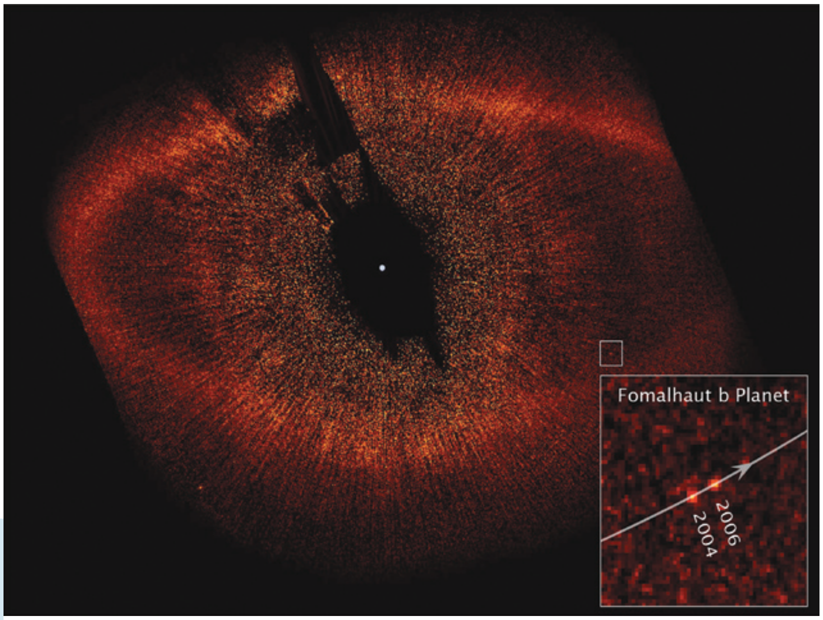
Currently, the barcoded information is “read” with a common laboratory scanner that is also used for gene- and protein-expression studies. “But it should be very easy to design something like a supermarket UPC scanner to read the information,” making the process even more user-friendly, says postdoc Rong Fan, the first author on the paper.

The paper’s other authors are Alok Srivastava, a postdoc at the Institute for Systems Biology; Brian Yen, then a Caltech postdoc; postdoc Lidong Qin; grad students Habib Ahmad and Gabriel Kwong; and undergrads Chao Chao Liu and Julianne Gould. The work was funded by the National Cancer Institute and by the Institute for Collaborative Biotechnologies through a grant from the United States Army Research Office. —*KS* e&s

PLANET, HO!

A team of scientists including two Caltech alumni and a brace of JPL staffers have used the Hubble Space Telescope to take the first-ever visible-light photo of a planet orbiting another star—Fomalhaut, a bright star about 25 light-years from Earth. The planet, estimated to be no more than three times Jupiter’s mass, was found by comparing pictures of the debris ring around Fomalhaut taken two years apart. The first picture revealed several bright points in the ring that might have been planets; the second one showed one of them had moved.

The team includes UC Berkeley professors Paul Kalas, James Graham, and Eugene Chiang (PhD ’00), Berkeley grad student Edwin Kite, Mark Clampin of NASA’s Goddard Space Flight Center, Michael Fitzgerald of Lawrence Livermore National Laboratory, and JPL’s Karl Stapelfeldt (PhD ’91) and John Krist. —*DS* e&s



Fomalhaut has been a prime target for planet hunters ever since JPL’s Infrared Astronomy Satellite (IRAS) found a region of excessive dust around it in the early ’80s. This image was taken using the coronagraph in Hubble’s Advanced Camera for Surveys, which blocks out the bright light of the central star (here represented by the white dot). The radial streaks in the image are glare from the star, but the bright ring is real dust, and its off-center shape suggested to Kalas that a planet might be “shepherding” it. That planet, Fomalhaut b, is about one billion times fainter than its star, has a calculated orbital period of 872 years, and is roughly 18 billion kilometers from its star, or 10 times the distance from Saturn to the sun.

Opposite, left to right: Ripples on an atomically smooth graphite surface. These images were taken 200 nanoseconds (billionths of a second), 500 nanoseconds, 10 microseconds (millionths of a second), and 30 microseconds after a laser set the atoms in motion.

PASS THE POPCORN

More than a century ago, movies brought still photographs to life. Now the same thing has been done at Caltech on the atomic scale—the first real-time, real-space views of fleeting changes on a tract of crystalline real estate barely a billionth of a meter on edge. The making of such "movies" starring gold and graphite is described in the November 21 issue of *Science*. (The movies themselves can be found at http://ust.caltech.edu/movie_gallery/.) The new technique, dubbed four-dimensional (4D) electron microscopy, was developed at Caltech's Physical Biology Center for Ultrafast Science and Technology, directed by Ahmed Zewail, the Pauling Professor of Chemistry and professor of physics, and winner of the 1999 Nobel Prize in Chemistry.

Zewail was awarded the Nobel Prize for pioneering the science of femtochemistry, the use of ultrashort laser flashes to observe fundamental chemical reactions—atoms uniting into molecules, or breaking apart back into atoms—occurring at femtosecond timescales. (A femtosecond, or 10^{-15} seconds, is one millionth of a billionth of a second. To grasp how incredibly evanescent this is, consider that it takes a beam of light one second to travel from Earth to the moon. In a femtosecond, light goes one one-hundredth the thickness of your eyelash.) The work "captured atoms and molecules in motion," Zewail says, akin to the freeze-frame sequences snapped by 19th-century photographer Eadweard Muybridge of a trotting horse that proved for the first time that it does indeed lift all four hooves off the ground as it trots.

Snapshots of molecules in motion "gave us the time dimension," Zewail says, "but what we didn't have was the dimensions of space, the structure. We didn't know what the horse looked like. Did it have a long tail? Beautiful eyes? My dream since 1999 was to come up with a way to look not just at time but also at the spatial domain."

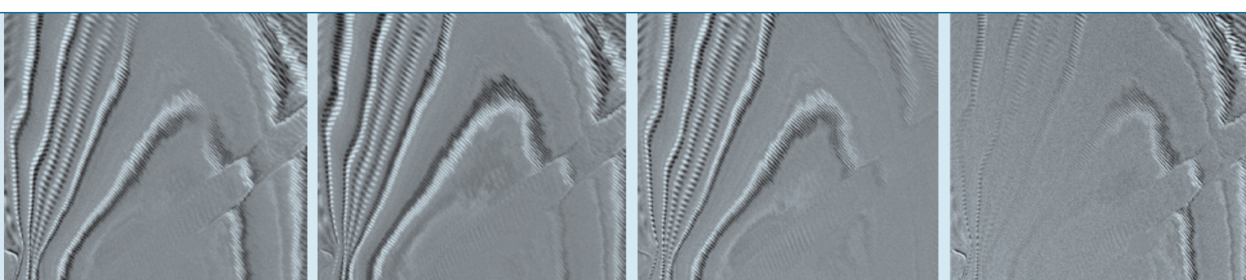
The system uses a high-resolution transmission electron microscope, which "illuminates" the specimen with a stream of electrons to produce an image. In order to be "seen," a feature on the specimen must be significantly larger than the wavelength of the "light"—in this case, the electron beam—illuminating it. Because the wavelength of an electron shrinks as its velocity increases, very tiny things indeed can be seen with electrons that have been accelerated to dizzying speeds.

But this isn't enough—the electrons have to be carefully doled out so that they arrive at the sample at specific times. This is achieved by precisely timed laser pulses that individually control every electron's trajectory through time and space.

The image produced by each electron represents a femtosecond still photo. Like the frames in a film, many millions of such images can be assembled into a digital movie of atomic-scale motion.

Zewail and colleagues applied the technique to superthin sheets of gold and graphite, the form of carbon in pencil lead. They would zap the specimen with a femtosecond laser pulse that caused heat-induced stress in the material, and then watch as the atoms moved in response.

Graphite is particularly interesting because its atoms are locked into sheet-like arrays. These sheets remain highly crystalline even when not much thicker than a single atom, making them a potentially very important item in the nanoengineer's toolkit—for example, as ultrathin resonators. These experiments were done on samples some 200 atoms thick and a few

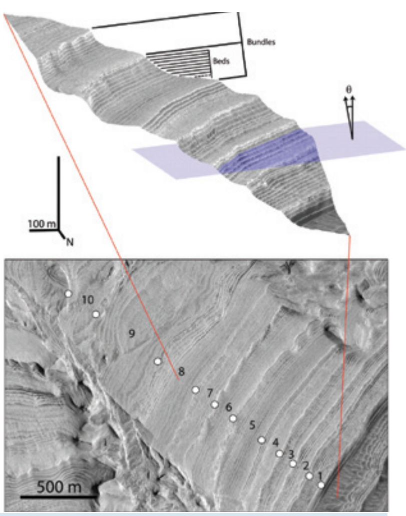


From Oh Hoon Kwon, et al., *Nano Letters*, Vol. 8, No. 11, pp. 3557–62, November 2008. © Copyright 2008, American Chemical Society.

millionths of a meter wide. Three different behaviors were found, on three different timescales. “The behavior evolves with time,” says postdoc Brett Barwick, the lead author of the *Science* paper. “If you could keep watching the same sample, you’d see it do all three things, one after the other.”

When the atoms first get blasted by the laser, the heat sets them into random individual vibrations. But neighboring atoms begin to synchronize with each other on femtosecond timescales, and in picoseconds (a picosecond is 10^{-12} seconds, or one thousandth of a billionth of a second), sound waves begin to reverberate back and forth through the sample’s thickness. Each little patch of the sample’s surface vibrates at its own frequency, but a companion paper by postdoc Oh Hoon Kwon in the November 2008 issue of *Nano Letters* describes how, as the picoseconds drag into microseconds (millionths of a second), the patches slowly lock into phase with one another, and the oscillations travel the width of the sample, going back and forth across the surface in a heartbeat-like “drumming.” The papers were co-authored with J. Spencer Baskin (PhD ’90), senior scientist; Hyun Soon Park, senior postdoctoral scholar; and Zewail.

“With this 4D imaging technique the atomic-scale motions that lead to structural, morphological, and nanomechanical phenomena, can now be visualized directly, and hopefully understood,” says Zewail, who is now expanding the research to biological imaging within cells in collaboration with Associate Professor of Biology Grant Jensen. (See *E&S* 2006, No. 2.) The researchers are looking at things such as proteins and ribosomes—the cellular machinery that makes proteins—trying to track their component parts as they move. —*KS/DS* e&s



Stereographic analysis of photos from the HiRISE camera on the Mars Reconnaissance Orbiter allowed the topography of Becquerel crater (8° W, 22° N) to be reconstructed. Ten “bundles” of layered beds can be seen here. The individual beds are 3.6 ± 1 meters thick, and the bundles are 36 ± 9 meters thick.

ICE AGES ON MARS?

Some layered deposits on Mars may have been caused by regular variations in the planet’s tilt. On Earth, similar “astronomical forcing” drives ice-age cycles. Grad student Kevin Lewis and Oded Aharonson, associate professor of planetary science, along with John Grotzinger, the Jones Professor of Geology, examined outcrops in four craters in the Arabia Terra region and found that each set of layers have similar thicknesses and similar features.

The scientists propose that each layer was formed over a period of about 100,000 years, corresponding to a change in the tilt of Mars’s axis by tens of degrees analogous to the (smaller) Milankovitch cycles on Earth. When the axis is near vertical, the sun hovers over the equator and the poles stay cold. This would cause volatiles in the atmosphere, like water and carbon dioxide, to migrate poleward, where they’d be locked up as ice.

As the axis tilts, the poles get relatively more sunlight, and those materials would migrate away. “If you move carbon dioxide away from the poles, the atmospheric pressure would increase, which may cause a difference in the ability of winds to transport and deposit sand,” explaining the layering, Aharonson says.

Groups of 10 layers are bundled into larger units that were laid down over approximately million-year periods. This corresponds to a known modulation in the tilt cycle caused by solar-system dynamics.

Lewis is the lead author on the paper, which appeared in the December 5 issue of *Science*. Other authors include Randolph Kirk (MS ’84, PhD ’87), of the U.S. Geological Survey; Alfred McEwen of the University of Arizona, and Caltech staff member Terry-Ann Suer. —*KS* e&s

The Friday morning crew. Putnam, in a brown baseball cap, is seated in the foreground. Kelzenberg is standing second from right, wearing a cowboy hat.

STUDENTS GO SOLAR

Even as the Caltech administration launches big-ticket sustainability projects, there are grassroots endeavors as well. The roof of the Watson Laboratories of Applied Physics sprouted a 72-panel solar array the week before Thanksgiving, thanks to the newly formed Caltech Student Solar Initiative (CSSI). About 80 undergrads, grad students, and postdocs laid out solar panels, bolted them to their supports, wired them up, and schlepped cinder blocks between November 19 and 21—"We had as many people as we could manage," says Morgan Putnam (MS '08), the project leader.

Putnam and Michael Kelzenberg (MS '06), the lead project engineer, are keenly interested in solar power. When not clambering around on rooftops, they're grad students in the lab of Harry Atwater, the Hughes Professor and professor of applied physics and materials science, and work on developing silicon microwires that could be used as solar cells. (The Atwater group, coincidentally, lives in the Watson Labs.)

The project was student-designed and executed as much as possible. Kelzenberg handled the array layout and wiring, while Putnam worked out the details of the cinderblock ballasting system that keeps the arrays in place without having to drill holes in the roof. Says Kelzenberg, "Students contacted suppliers, designed the array, and [junior] Daryl Coleman filed the application for the rebate" with Pasadena Water & Power that will pay back about half of the $118,000 materials and installation cost.

Grad student Amy Hofmann (MS '08) organized and submitted the CSSI's application to the Moore-Hufstedler Fund for Student Life, which will cover another $32,000 of the initial installation costs. Says Putnam, "This was a large task, and Amy did a great job of assembling information from a large number of sources to produce a final product." Caltech's Facilities Department will cover the rest of the cost, while the Graduate Student Council chipped in $1,000 to feed the volunteers during the installation.

Facilities, particularly Mike Anchondo, the head of Caltech's electrical shop, donated a lot of help and expertise, says Kelzenberg. For example, Narinder "Nick" Grewal, the electrical engineer for physical plant, double-checked the rebate application. Adds Putnam, "CSSI offers its sincere thanks for the generous support of Caltech Facilities. Nick Grewal and Mike Anchondo helped field electrical questions. Don Thomas helped with roofing concerns. Kalman 'Lee' Benuska handled seismic and wind-loading concerns. Bill Irwin and Kenneth Hargreaves helped with long-term planning and project planning. Most importantly, Jim Cowell [Associate VP, Facilities] and John Onderdonk [Sustainability Program manager] fielded questions across a spectrum of topics. Their offices were always open."

"This is the only Caltech-owned solar array on campus," says Kelzenberg. "There are larger, more expensive arrays, such as the one on the roof of the Holliston parking structure, but Caltech actually leases these roof areas to outside companies, who own the solar panels. Caltech then buys the power. Here, Caltech owns the panels, and all the power they produce."

The array will put out an estimated 13.7 kilowatts at peak—that is, at noon on a sunny day. Year round, this is expected to amount to about 23,000 kilowatt-hours of juice. The CSSI plans to sell this green energy in the form of 150 Renewable Energy Credits for 150 kilowatts each—

Atwater postdocs Dierdre O'Carroll and Marina Leite install the support structure on the back of a solar panel.

"enough to run your laptop for one year," says Putnam—which students can buy for $20. The proceeds will go into a student sustainability account to fund future projects.

Including the Holliston parking structure array, which went online November 4, Caltech Facilities plans to install 1.4 megawatts of solar power over the next 12 months. These arrays will be atop the two Wilson Avenue parking structures, the Braun Athletic Center, the Infrared Processing and Analysis Center, Baxter Hall of the Humanities and Social Sciences, and the new Cahill Center for Astronomy and Astrophysics.

The CSSI hopes to add to the total, using the roofs of smaller, more oddly shaped buildings. Says Putnam, "These small projects are very labor-intensive, and therefore amenable to student activity. And with the group we have now trained, we could do a lot more very easily." Kelzenberg agrees, "We could do it again with half of the effort, if we get more funding. There are lots of smaller roofs all over campus that students could do this way." *—DS* e&s

NEW ENERGY FOR MECHANICAL ENGINEERING

Author Tom Friedman leveled his gaze at a lunchtime assemblage of Caltech faculty, students, and friends and threw down the gauntlet: "Only Caltechs are going to get us out of this problem," he said. He was talking about three problems, really, that he views as one giant Gordian knot: climate change, the global economic crisis, and America's dented world leadership. During his most recent campus visit, the writer of the best sellers *Hot, Flat, and Crowded* and *The World Is Flat*, not to mention innumerable "most e-mailed" articles in the *New York Times*, joined Argyros Professor and professor of chemistry Nate Lewis (BS, MS '77)—a principal investigator in the Caltech Center for Sustainable Energy Research (CCSER)—in a conversation about these problems. Friedman commented that America's research universities could help lead the way out of all three with one bold stroke. He's calling the solution ET—not the alien darling of the '80s, but energy technology, the challenge of the Aughts. "The motto for America," he quipped, "should be 'Invent, Baby, Invent.'"

Invent we will. Caltech already boasts programs like CCSER, which focuses on solar energy, and the Linde Center for Global Environmental Science. These have now been joined by an Energy Engineering Initiative, which was funded as part of a $10 million gift from the Gates Frontiers Fund this September that established the Charles C. Gates Center for Mechanical Engineering.

"One is tempted to say that energy is *the* technological challenge facing engineering," says Kaushik Bhattacharya, professor of mechanics and materials science and executive officer for mechanical engineering. "The scale and magnitude of the numbers involved make the problem very hard to grapple with—the amount of energy used, the time horizons on which investments are made. Decisions we're making today will tie our hands in the future. The challenges we're facing are such that we have to invest in completely new technologies, but at the same time, we have to address

The solar array atop the Holliston parking structure, installed and operated by EI Solutions, will crank out some 320,000 kilowatt-hours (kWh) per year, earning a $0.632/kWh rebate from Pasadena Water & Power—and it provides shaded rooftop parking.

the intermediate time scale."

Solving these problems requires expertise in many disciplines, but that only whets the appetite of Caltech's ME faculty, which has a staggering intellectual diversity. Fourteen of the 19 professors have joint appointments in other fields, from geophysics to materials science.

The initiative will attract new faculty, students, and postdoctoral scholars with their own ideas and research emphases. It will also expand existing ME interests in areas such as fuel cells and nuclear energy.

Professor of Mechanical Engineering and Applied Physics Dave Goodwin's group models and develops materials for advanced fuel cells, which can be used for stationary power generation and for automotive power. Goodwin's models—created with a widely used software package called Cantera that he developed to model chemically reacting flows—predict that solid-oxide fuel cells (SOFCs) could be vastly improved by engineering their structures at micrometer and nanometer scales. In SOFCs, oxygen ions flow through a ceramic electrolyte to oxidize hydrogen in the fuel. The cells make electricity from a variety of fuels already well established in the market, including methanol, ethanol, methane, propane, coal-derived syngas, or even diesel reformate. To maximize the amount of electricity produced from these fuels at the power-plant scale, Goodwin's group is engineering the architecture of the electrodes using nanowires and nanoparticles to build a three-dimensional, ion-conducting lattice framework that provides easy ion flow and allows rapid gas transport through the electrode. Through their efforts, in combination with those of researchers in CCSER and other Caltech programs, ME researchers hope that fuel cells will become an ideal source of electricity: superefficient, fuel-flexible, and, eventually, powered by clean, renewable fuels such as hydrogen electrolyzed from water by sunlight (see *E&S* No. 2, 2008).

Several faculty members are addressing what Bhattacharya calls the "show-stopping problems" associated with nuclear energy. With Michael Ortiz, the Hayman Professor of Aeronautics and Mechanical Engineering, Bhattacharya is working to make reactor vessels last longer in the face of bombardment by high-energy neutrons. This would remove a bottleneck in building reactors that reprocess spent uranium to generate their own fuel. Meanwhile, Hayman Professor of Mechanical Engineering Chris Brennen's work improves several energy technologies, including nuclear reactors. He wrote the book (the two key books, actually) on cavitating flows, whose tiny bubbles collapse with trip-hammer force to chew through valve, propeller, engine, turbine, and pump blades. And Joe Shepherd (PhD '81), the Johnson Professor of Aeronautics and professor of mechanical engineering, studies what happens when things go seriously wrong—from deflagrations, ordinary fires that spread at subsonic speed through heat transfer, to detonations, their supersonic kin that spread through shock waves.

The initiative will also support research not yet under way. For instance, engineers will be able to collaborate with geophysicists and atmospheric scientists on carbon sequestration—keeping carbon out of the atmosphere by storing it underground—and with information science and technology experts on designing smart power grids, which use digital technology such as sensors and two-way communication to improve the transmission and distribution of electricity from myriad decentralized sources, bypassing traffic jams and cable breaks. Graduate students and undergraduates interested in wind power, solar-thermal energy, and other technologies will be able to design research projects based in ME that draw on talent and resources across several academic divisions.

The Gates Frontiers Fund gift will help support a planned renovation of the postwar Franklin Thomas Laboratory into a state-of-the-art research and teaching facility. Taking a leaf from the successful renovation of GALCIT's home (see *E&S* No. 1, 2008), Caltech plans to rehabilitate the landmark building rather than build a new lab. Still, another $10 million will be needed to recruit key people and complete the renovation.

The late Charles C. Gates, a Caltech trustee for 25 years, felt that Caltech excelled at solving complex problems and getting the solutions to market, and he relished the faculty's disregard for disciplinary boundaries. His daughter, Diane G. Wallach, remembers that he kept up with every aspect of science at Caltech, reading each issue of this magazine cover to cover. A conservationist who loved the outdoors, Gates would have appreciated the environmental aims of the Energy Engineering Initiative. Even more, though, he would have liked its multifaceted approach. "My father felt that Caltech did things differently than other prominent universities. He liked the concentration of energy going into science and technology, and loved Caltech's focus on the hard sciences. He was an engineer himself, and believed that mechanical engineering should cut across all the disciplines, that we have to get people from all these areas into the same room, get them talking to each other to solve problems. This gift will help make that happen." —*AW* e&s

BECALMED?

The solar wind has apparently become just a solar breeze. New data from the Ulysses spacecraft shows that the solar wind has lost power, which has exposed the solar system to more cosmic rays. The data also reveals that the wind and the sun's magnetic field are more intimately related than previously thought, shedding light on how the wind is produced. "Ulysses has provided a new constraint on the origin of the solar wind," says JPL's Ed Smith, project scientist for the mission. "The data provides us with a new view of what's going on at the source."

Made of charged particles gushing from the sun's outer atmosphere—called the corona—at hundreds of kilometers per second, the solar wind reaches billions of kilometers away. The sun's magnetic field, however, keeps the particles trapped within the corona at first, preventing the wind from escaping. Scientists used to think that the pressure of the wind would grow until it broke free from the magnetic field, like a flock of sheep escaping by pushing open the gate to their pen.

But Ulysses is finding that the solar-wind flux—that is, how many particles spew out per second—is proportional to the strength of the sun's magnetic field. This relationship suggests a different understanding of how the wind blows. "The magnetic field plays not only an important role, but a dominant role," Smith explains. Magnetic field lines emanate from the sun and curve back toward it, forming loops that hold in the wind's charged

FOUR FOR TWENTY

This year's Discover 50, an annual list of the "best brains in science" published by *Discover* magazine, features four Caltech "young visionaries" in the article titled "20 Under 40"—Assistant Professor of Biology and Applied Physics Michael Elowitz; Assistant Professor of Biology Sarkis Mazmanian; Associate Professor of Environmental Science and Engineering Tapio Schneider; and Assistant Professor of Electrical Engineering and Bioengineering Changhuei Yang.

Elowitz designs and builds cellular "circuits," as described in *E&S* No. 1, 2008. Mazmanian studies the "good" bacteria that live in our guts and symbiotically help our immune systems keep us healthy. Schneider makes computer models of the complex effects of atmospheric turbulence and heat transfer on global climate change. And Yang has built a lensless microscope-on-a-chip that could be incorporated into a pocket-sized device for analyzing blood samples or potable water supplies in the developing world.

UCLA, Harvard, and MIT were the only other institutions having more than one person on the list, with two each.—*DS* e&s

particles. The sun's field is irregular and dynamic, however, and sometimes those loops break. When they do, they release the wind into space. In other words, the gate opens by itself to let the sheep roam free. The solar-wind flux is analogous to the number of sheep, and the strength of the magnetic field is analogous to how wide the gate opens. The correlation between the wind and magnetic field must now be taken into account in future computer models, Smith says.

Once released, the wind reaches far beyond the edge of the solar system, where it slams into particles from other stars—the interstellar wind—forming the boundary of a huge bubble called the heliosphere. Because it's kept inflated by the solar wind, the heliosphere shields the solar system from cosmic rays.

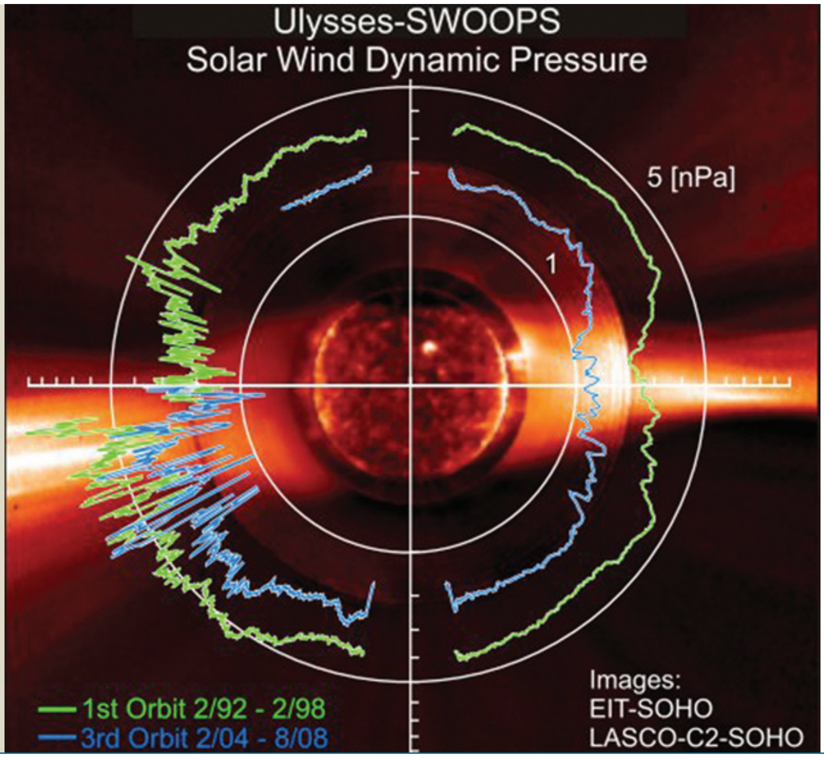
In September, Ulysses scientists announced that the pressure of the solar wind has waned 20 percent since the mid-1990s. The wind hasn't slowed down much, losing only 3 percent of its speed, but it's 13 percent cooler and 20 percent less dense. The lack of pressure causes the heliosphere to deflate and weaken, allowing more cosmic rays to pass through. The sun's magnetic field has also diminished by 30 percent, further crippling the heliosphere.

We're protected by Earth's atmosphere and magnetic field, so those of us on the ground don't have anything to worry about. But a surge in cosmic rays could pose a threat to astronauts, who would need more protection against the damaging radiation, as would spacecraft and satellites in high-Earth orbit.

A shrunken heliosphere also explains Voyager 2's findings. In the beginning of September 2007, the spacecraft crossed the heliosphere boundary, called the termination shock, earlier than researchers had anticipated.

It's unclear what a quieter solar wind means. After all, scientists have only been studying the wind since the dawn of the space age a mere 50 years ago. Launched in 1990 and operated from JPL by NASA and ESA, Ulysses circles the sun, studying how solar activity changes along different solar latitudes, from pole to pole.
—*MW* e&s

The Ulysses spacecraft is in a polar orbit around the sun, allowing complete three-dimensional observations of the solar wind and the near-solar region to be made. An instrument called Solar Wind Observations Over the Poles of the Sun (SWOOPS) records the solar wind's "dynamic pressure," a measure of its kinetic energy. The outer white circle around the sun represents a pressure of five nanopascals, or billionths of a pascal; the inner one is one nanopascal. (A pascal, of course, is a force of one newton per square meter. But you knew that.) The colored lines trace the dynamic pressures observed.
The background images of the sun are from NASA's Solar and Heliospheric Observatory (SOHO).



Left: This rendering of data from JPL's Atmospheric Infrared Sounder (AIRS) shows local carbon dioxide levels in July 2003 at an altitude of eight kilometers. Lower than average concentrations are shown in blue and higher than average concentrations are shown in red.

Global Change and Energy: A Path Forward

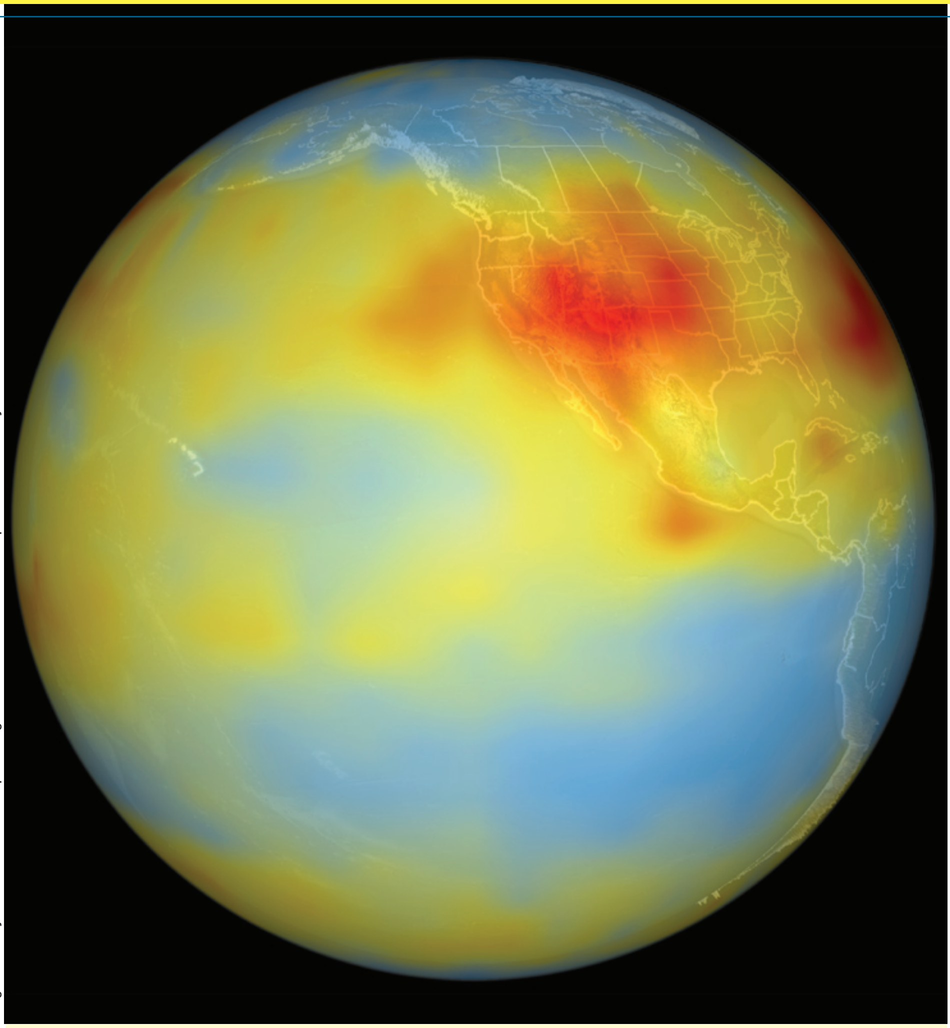


Image courtesy of NASA/Goddard Space Flight Center and NASA/Jet Propulsion Laboratory Scientific Visualization Studio

Can we keep the lights on in New York without inundating Bangladesh? JPL's chief technologist offers some thoughts.

The greenhouse effect is good for you. Without it, Earth's temperature would be like the moon's—they're the same distance from the sun. But it's a bit like aspirin—one aspirin is good, but 20 may kill you. Earth's atmosphere contains a few hundred parts per million of carbon dioxide, and just a whiff of methane—both powerful greenhouse gases. We know what their levels have been over the last 650,000 years or so, by analyzing ice cores from Antarctica and Greenland. These values have increased dramatically in the last couple hundred years, with the CO_2 increase traceable to fossil-fuel burning. The heat-trapping properties of these gases are well understood and their increasing concentration is altering the balance between the solar radiation coming in and the thermal radiation going out. The only way our planet can respond to this imbalance is by raising its temperature, so that it can radiate the excess heat more effectively.

The estimated radiative imbalance is somewhere between one-half and two watts per square meter. We can visualize a one-watt-per-square-meter imbalance by imagining dividing Earth's entire surface—land and sea—into squares 10 meters on edge, and lighting a 100-watt bulb inside each one, as Jim Hansen of the Goddard Institute for Space Studies has noted. The heat from those 100-watt bulbs is warming our planet.

But the effect is not immediate. Consider a large, well-insulated boiler. A relatively small flame may be all that's needed to keep the water hot. If we wrap another two-inch

By Paul E. Dimotakis

insulation blanket around the boiler, the rate of temperature rise will be the flame's heat output divided by the boiler's heat capacity. With a little flame and a lot of water, this rise will be slow but sure, until a new equilibrium is restored. For Earth, this lag is some 30 to 40 years—longer if we wait for the temperature to rise everywhere. Thus the present radiative imbalance will increase Earth's temperature further, even if we were to quit emitting CO_2 today.

The debate about the interrelationship between our current CO_2 emissions and our changing weather patterns and climate continues, but the geologic record provides examples of cause and effect. About 50 million years ago, India—moving at a speed of almost a foot per year!—was colliding with Asia, thrusting the Himalayas up and grinding over beds of limestone and other carbonate rocks. Carbon dioxide was released, and the resulting temperature rise was enough to melt the Antarctic ice—all of it. This influx of fresh water and the expansion of the warming ocean raised the sea level by some 75 meters above today's levels. Later, as CO_2 was slowly absorbed by the oceans and by vegetation, temperatures dropped. Antarctica froze over again about 30 million years ago and has been frozen since.

Carbon dioxide is a problem because it is virtually indestructible. It's the most oxidized form of carbon. It is no accident that Mars's atmosphere today is carbon dioxide—it's the only molecule that can survive the intense bombardment from the solar wind. Most of Venus's atmosphere is also carbon dioxide. On the other hand, methane, a more powerful greenhouse gas per molecule, is destroyed in about a decade by chemical reactions in our atmosphere.

The discussion about human-caused climate change has been difficult in this country. On the one side, we have the evangelists for the cause, and on the other, people who consider it to be the greatest hoax ever perpetrated. If the two extremes can be persuaded to be quiet, we may have the rational public discourse that the challenge merits. JPL, Caltech, and many other institutions have been contributing data and ideas to the discussion, some of which I will summarize here. I will also describe a path forward. At this point in the debate, one cannot announce that the sky is falling without offering a vision for how to get out from under it.

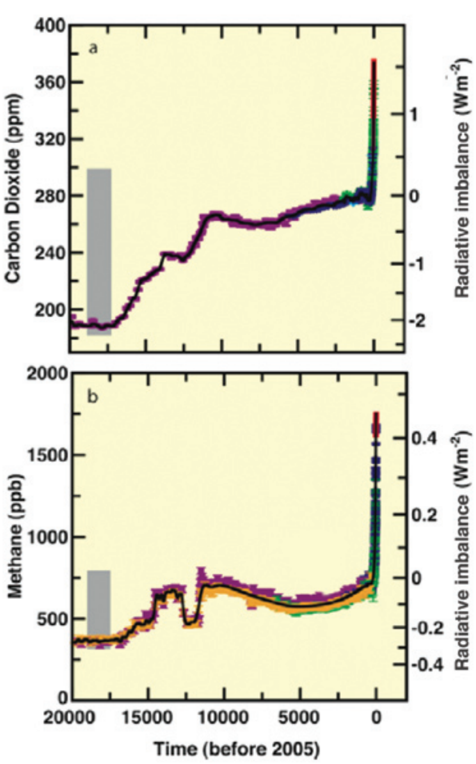
There are three guiding questions that can help our thinking as we look ahead.

QUESTION ONE: WHAT'S THE PROBLEM?

How much CO_2 can our planet's systems safely absorb? There are actually four parts to this question. First, at what rate is CO_2 absorbed by natural long-term repositories, of which there are only a few? Carbonate rocks are laid down in warm, shallow oceans. Rocks on land, particularly peridotites, can also absorb CO_2. Importantly, CO_2 also dissolves in seawater, particularly the cold water of the deep oceans. Second, to what rate must we reduce CO_2 emissions to stay below some acceptable threshold level? Third, what *is* an acceptable threshold level? And finally, what do we mean by *acceptable*?

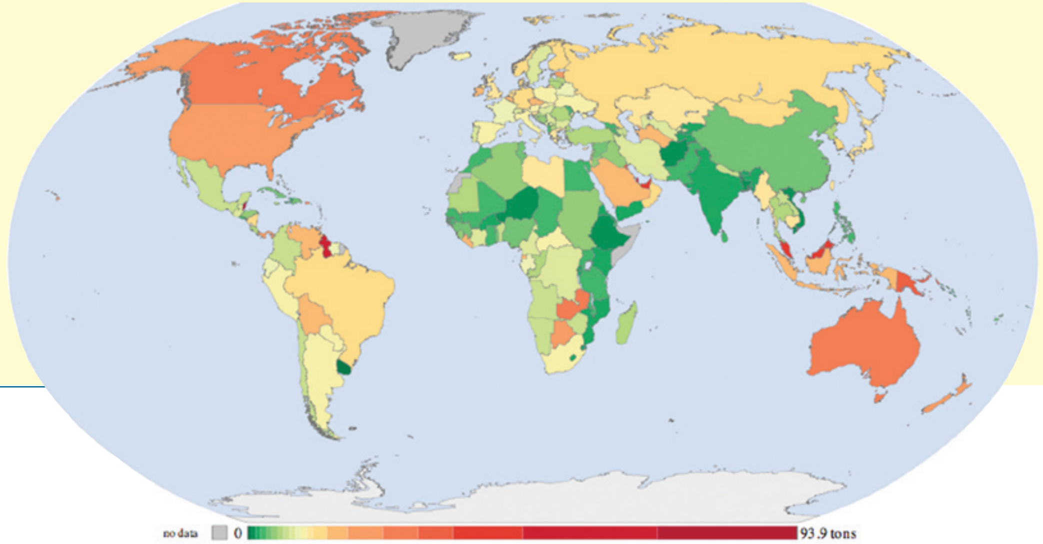
The first three are global questions, but the fourth is local. Consider the plight of Kiribati, a Pacific archipelago whose highest elevation is only six feet above sea level. They are not going to make it, so Kiribati's president, Anote Tong, asked the world community to help relocate the entire population—about 100,000 people. Next to go may be the Maldives, whose 300,000 or so residents are also looking for a new home, then perhaps the rather more populous Bangladesh.

One could argue for a cost-benefit analysis. If the price of climate change, such as from sea-level rise, for example, is the loss of less than 1 percent of the world's Gross Domestic Product, perhaps that's acceptable if avoiding it is more costly. However, the costs are not spread uniformly—it may be an all-or-nothing proposition for the losers. Bangladesh's GDP is much less than



The left-hand scale shows the atmospheric concentrations of carbon dioxide (top) and methane (bottom) frozen into the ice and snow of Antarctica and Greenland over the last 20,000 years. The gray bars span the range of values recorded over the last 650,000 years. The right-hand scale shows the estimated radiative imbalance, or atmospheric heating, attributable to that gas at that concentration. Adapted from figure TS.2 of *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.*

Per capita carbon-dioxide emissions in the year 2000, based on the World Resource Institute's Climate Analysis Indicators Tool 4.0 database. This includes estimates of the effects of deforestation and agriculture as well as the burning of fossil fuels. Map created by Vinnie Burgoo, Wikimedia. Image from http://commons.wikimedia.org/wiki/Image:GHG_per_capita_2000.svg



1 percent of the world's GDP. Is it okay to tell the Bangladeshis, "Sorry, you're out?" I doubt very much they'd see it that way. Incidentally, California may not be far behind Bangladesh—but not due to sea-level rise, as we'll see. California is more than 3 percent of the world's GDP and a little nearer and dearer to our hearts.

Atmospheric CO_2 is accumulating at a rate of two parts per million per year, a rate that is itself increasing. However, there's considerable uncertainty about what the acceptable rate is—from 40 percent of our current emission rate, down to 0.1 percent. (The first number comes from noting that the atmospheric accumulation can be accounted for by assuming that about 57 percent of what's emitted hangs around in the air. The second number reflects the fact that the mixing time between the surface and deep oceans is some 1,000 to 2,000 years.) Even though policy makers are used to dealing with uncertainty, this one is too large to plan around, especially if we also say we won't see the effect for 30 to 40 years. We need to try and quantify the uncertainty in our forecasts, which requires modeling Earth's climate a lot better than we do now. When we give policy makers a projection, we need to also tell them what its uncertainty is and why we think so, a little like hurricane-track projections. As scientists, we have not done all we should to help the people charged with making decisions.

QUESTION TWO: HOW CAN WE FIX THE PROBLEM?

Continuing to burn fossil fuels unabated will eventually exceed any conceivable acceptable levels. Some scientists believe the present CO_2 level of 380–385 parts per million is already too high. We should also understand that it doesn't make any difference who emits the CO_2—China, Russia, the U.S., India, Europe—so international agreements will likely be required. How can we implement, monitor, and enforce them? Fortunately, we have examples to guide us.

In 1987, the Montreal Protocol banned ozone-depleting chemicals. The chemical industry was initially dead set against it—selling chlorofluorocarbons was good for business. Things were going nowhere until a bright engineer realized that an agreement would make every refrigerant then in use around the world illegal—plus the present patents were expiring—and who would produce their replacements? Well, the selfsame chemical industry, of course!

A closer analog may be the Comprehensive Nuclear Test Ban of 1996, designed to slow the proliferation of atomic weapons. The signatories rely on a remarkable system of networked land, sea, air, and space sensors, and are convinced that no nuclear explosion can be set off undetected. That's one key. The network is open—the sensors' calibrations and the data produced are accessible to all. If the network indicates a breach, there are agreed-upon procedures for on-site inspections. That's the other key—in case of doubt, you are entitled to see for yourself with your own Geiger counters, or whatnot. Trust, but verify.

So we have three ingredients. The agreement must be to the advantage of the signatories, there must be a way to monitor compliance, and there must be a mechanism for dealing with possible acts of noncompliance. Trillions of dollars would be at stake over an emissions treaty, and—I know this will come as a complete surprise—people cheat for less.

Creating the monitoring system will be a challenge, but it can probably be done. It's the political dimensions—making it advantageous to all—that's the hard part. China recently surpassed the United States in total CO_2 emissions. But China has four times our population. So negotiation is tricky. We cannot sternly say, "No Chinese person can emit more than a quarter of what every American does." The premier of India recently pledged *never* to exceed the per capita emissions of the advanced world. That's a safe bet, as India now emits a 30th of the United States, per person. Some developing nations argue that most accumulated CO_2 emissions are not their fault and that our emissions have led to our prosperity. Therefore, we should let them emit until they reach our per-person emissions, or even our *accumulated* per-person amounts, and *then* we can sit down to agree what to do.

QUESTION THREE: WHAT DO WE NEED FOR A SOLUTION?

Agreements are not solutions. As George Olah of USC said at a JPL seminar, imagine a treaty to ban cancer. Who's against banning cancer? Every nation will sign. Of course, nothing would happen because we don't know how to do it, at least not yet.

The global energy problem is almost unfathomably large, as Nate Lewis [BS, MS '77, the Argyros Professor and professor of chemistry] explained in *E&S* 2007, Number 2. Worldwide fossil-fuel energy consumption is 13 terawatts, or 13 trillion watts, on average, and increasing. Each of the two reactors at the San Onofre nuclear power plant near San Diego produces about a gigawatt, or one billion watts. Thirteen terawatts is 13,000 San Onofre reactors.

At this point in the debate, one cannot announce that the sky is falling without offering a vision for how to get out from under it.

Replacing just the world's electricity supply, which is four to five terawatts, in 30 years means bringing something like one such reactor on line every three days. Going electric for transportation, heating, and other energy uses—the whole shebang—requires one such reactor *per day* for 30 years. There isn't that much capital and there isn't that much uranium in the world (with the present nuclear-reactor technology), and, those two small issues aside, we don't know how to do that.

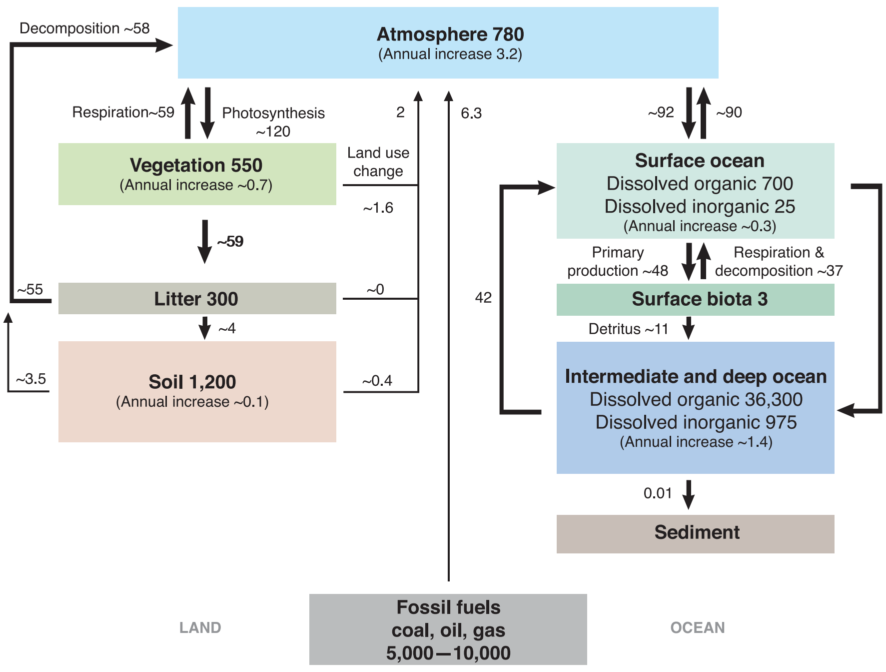
And there's one other difficulty. Time is of the essence. We have a ticking bomb and don't know how much time is on the dial—how long we have before we cross climatic "tipping points" of no return. Yet, transforming our energy infrastructure may have to wait for international agreements. People may not invest at the necessary scale in anticipation that someday, when the world hammers out a global pricing and regulatory system for the new energy economy, they'll have guessed right. Also, a mere 150 people got together to write the Montreal Protocol. There were 13,000 at the United Nations Climate Change Conference in Bali in December 2007. How does one get that many people to agree on *anything*?

TURNING THE BATTLESHIP AROUND

We don't know what a safe CO_2 level is and we can't turn a battleship around on a dime. If the world went cold turkey tomorrow, which will not happen, we'd still see about another 0.6°C, perhaps more, average global temperature rise—the same as the total increase over the last century—because of the time lag. This is why determining safe levels as soon as possible is important, so that we can plan, even as we do the best we can now to gain time. If we've already overshot, our strategy will be very different than if there's still headroom. We can envision ways of slowly replacing the existing CO_2-emitting infrastructure, but nobody has any plausible methods for getting large amounts of CO_2 out of the atmosphere—putting the proverbial genie back in the bottle.

Earth's carbon cycle is a delicate balance, as you can see below left. The oceans emit about 90 gigatons of carbon to the atmosphere per year, with CO_2 coming out of solution in the tropical Pacific, for example, where deep water rises and becomes warm. (Warm, low-pressure water can't hold as much dissolved CO_2 as cold, high-pressure water; another thing to think about as ocean temperatures increase.) At the same time, 92 gigatons per year are absorbed, mostly in the North Atlantic and around Antarctica, giving an estimated net absorption by the oceans of about two gigatons per year. Note that this is the difference of two large numbers, and a relatively small change or uncertainty in either of them will significantly alter that difference. On land, the balance is between photosynthesis that absorbs 120 and decomposition and respiration that put out about 117 gigatons per year. To make matters worse, "land-use change" is an amicable term for "deforestation." Deforestation adds another two gigatons per year at present, for a net absorption on land of about one gigaton per year—again, big numbers whose difference is vulnerable to small changes.

Burning fossil fuels adds 6.3 gigatons per year. There are 5,000 to 10,000 gigatons' worth left in the ground—even at the lower figure, more than enough to do us in. So



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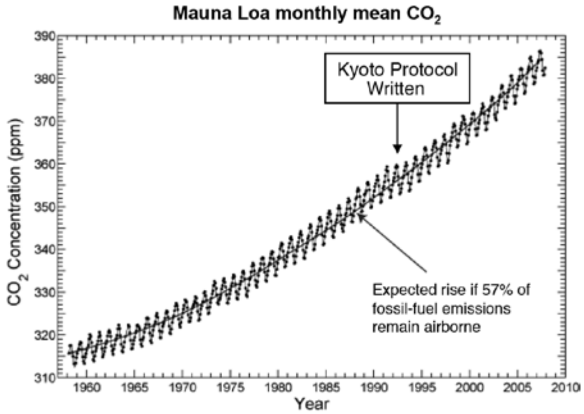
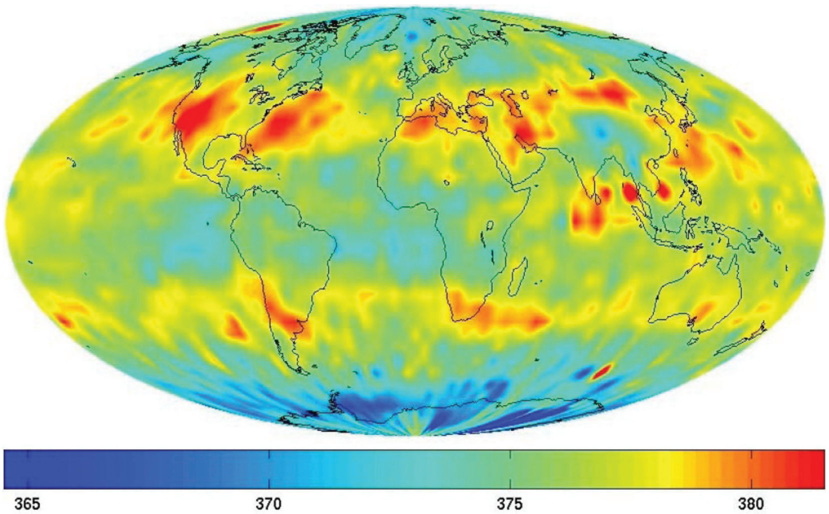
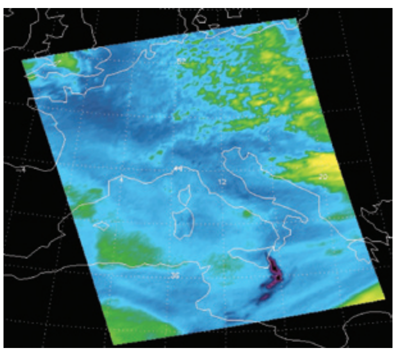
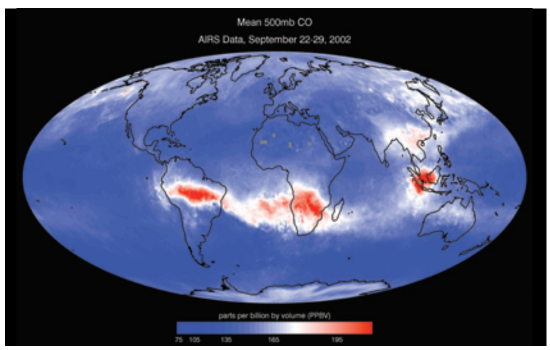
A top-level view of our planet's carbon cycle, using data from the 1990s. All numbers are in gigatons, or billions of tons, of carbon per year. Since the IPCC 2007 report was released, its most pessimistic predictions have been exceeded. Emissions from deforestation and burning fossil fuels have now risen to almost 10 gigatons per year.

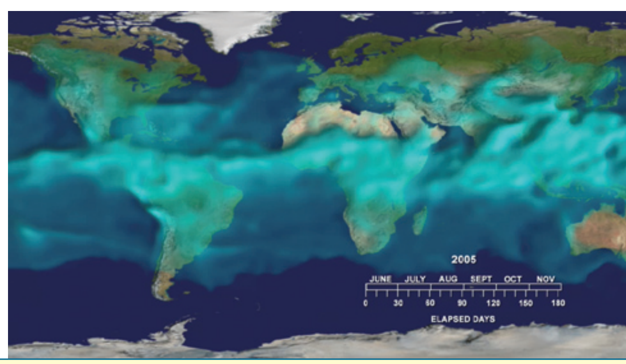


While a postdoc in geochemistry at Caltech (1953–56), Charles Keeling invented an instrument to measure CO_2 levels in air samples. In 1958, as a scientist at the Scripps Institution of Oceanography, he began measuring CO_2 levels at an altitude of eight kilometers on the slopes of Mauna Loa, Hawaii. The curve's sawtooth shape represents the planet "breathing"—plants in the northern hemisphere, where most of the land lies, draw extra carbon out of the air in the spring when they leaf out, only to release it in the fall. Keeling died in 2005, but the Mauna Loa program lives on, providing our longest continuous set of atmospheric CO_2 data. JPL's AIRS instrument takes data at the same altitude as the Mauna Loa site, allowing independent verification of the satellite readings.









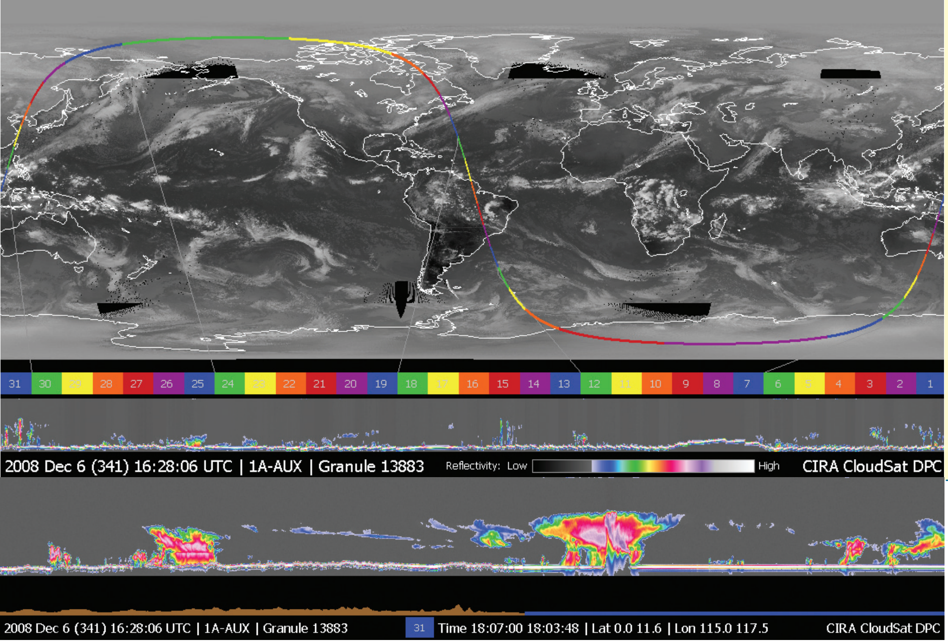
don't count on running out of oil and coal to solve the problem.

EYES IN THE SKY

JPL and other NASA centers are providing global data to climate modelers. I'll just briefly mention a few JPL instruments and missions here. The Atmospheric Infrared Sounder (AIRS), which flies on NASA's Aqua spacecraft as part of the Earth Observing System (EOS), is racing around Earth at about seven kilometers per second. AIRS gives CO_2 measurements that agree with ground-based measurements to within one part per million. This phenomenal accuracy is a great tribute to the AIRS team's scientists and engineers—it would be a challenge to match it in your laboratory. AIRS also measures temperature, carbon monoxide, ozone, water vapor, methane, sulfur dioxide, and dust.

AIRS measures CO_2 in the mid troposphere, about halfway up the atmospheric pressure scale. The red regions in the map at top left show excess concentrations of CO_2. The southern hemisphere is interesting because there are only two main regional anthropogenic sources of CO_2 there. One is in South Africa, which is very rich in coal. They burn a lot of it and convert part of it to liquid fuels. When an oil embargo was imposed on them during the apartheid years, they followed Germany's World War II example and built coal-to-liquid conversion plants. Unfortunately, turning coal into a liquid fuel takes about as much energy per gallon as

Above is a small sampling of some of the things AIRS sees, thanks to spectroscopic and other techniques invented and implemented by Moustafa Chahine, the AIRS lead scientist, and the AIRS team.
Top: Carbon dioxide levels in excess of 380 parts per million are seen in red in this data from July, 2003.
Middle, left: The sulfur dioxide plume (blue) of an erupting Mt. Etna on October 26, 2002.
Middle, right: Carbon monoxide levels on September 29, 2002, show slash-and-burn agricultural regions.
Bottom: A frame from a 3-D, time-lapse movie tracking the distribution of water vapor in the atmosphere.



Left: Radar data from a single CloudSat orbit. Each colored segment along the track in the upper image represents about three minutes. The bottom image shows Segment 31's overflight of Vietnam in more detail. The brown and blue bar across the very bottom shows altimetry data, with blue being ocean.
Below: The CloudSat spacecraft.

you get from burning the liquid, so you emit double the CO_2 of just burning oil. China is planning similar coal-to-liquid plants.

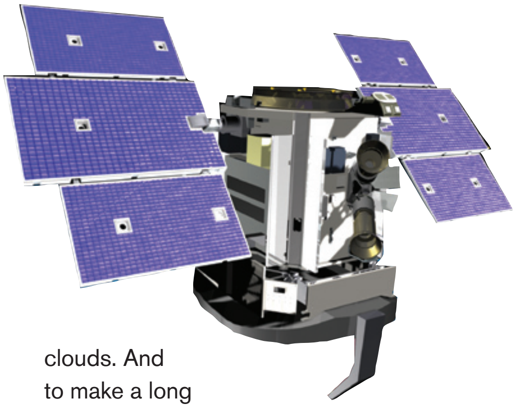
The other source is power plants in southeastern Australia, but you don't see a plume there because it's blown across the Pacific below the altitude where it's detectable by AIRS. The CO_2 then gets kicked up by the Andes in South America, where AIRS picks it up. The same thing may be happening over California. We get China's emissions, which are carried east and kicked up by the continental divide. CO_2 is a global problem—it's all one swimming pool, and there's no filter.

JPL's Orbiting Carbon Observatory (OCO), slated to launch in February 2009, will tell us about CO_2 near ground level. Every second, it will measure CO_2 levels to accuracies of one to two parts per million over a square 100 kilometers on edge, or roughly the distance from Santa Monica to San Bernardino. OCO—which I'm sure you chemists have noted is the structural formula for carbon dioxide, a linear molecule—will cover the entire state of California with six overflights that repeat every 16 days. OCO, in concert with AIRS and other instruments, will revolutionize our understanding of carbon dioxide's regional sources and sinks as well as its patterns of global transport.

JPL instruments also track other things important to climate. MLS, the Microwave Limb Sounder, flies on the Aura spacecraft, which is also part of EOS. MLS measures sea-surface temperatures to an accuracy of 1–2°C. It also continuously measures, to within a few percent, the amount of water vapor in a column from the planet's surface up to the edge of space. The condensation of rising water vapor from the warm ocean releases a lot of heat—the fuel of hurricanes. After Katrina hit, *New York Times* columnist Thomas Friedman asked in Caltech's Ramo Auditorium, did *we* do this? Scientists can't answer that question, but models do link hurricane intensity with sea-surface temperature. If you warm the ocean, you'd better run for cover during hurricane season. Columbus left Spain on August 3, 1492, and arrived in the Bahamas on October 12. You'd be ill-advised to try that today. The safe-crossing period for sailors starts ever later, pushed now to late November, perhaps early December, because with warmer tropical sea-surface temperatures the annual hurricane season lasts so much longer.

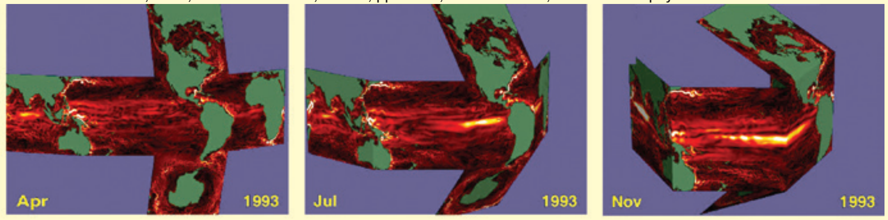
Sea-level rise is a valuable global thermometer. Josh Willis at JPL and collaborators at the Scripps Institution of Oceanography compared altimetry data from JPL's Jason-1 oceanographic satellite, built in collaboration with France, with temperature readings from about 3,000 floats bobbing up and down around the world's oceans. Temperature data show that the water's thermal expansion is contributing about 1.3 millimeters per year, but the total rise observed from space is about 3.4 millimeters per year. The difference is fresh meltwater from continental ice packs. Melting sea ice doesn't raise ocean height, as Archimedes explained some time ago. But if you melt ice on land, the runoff does.

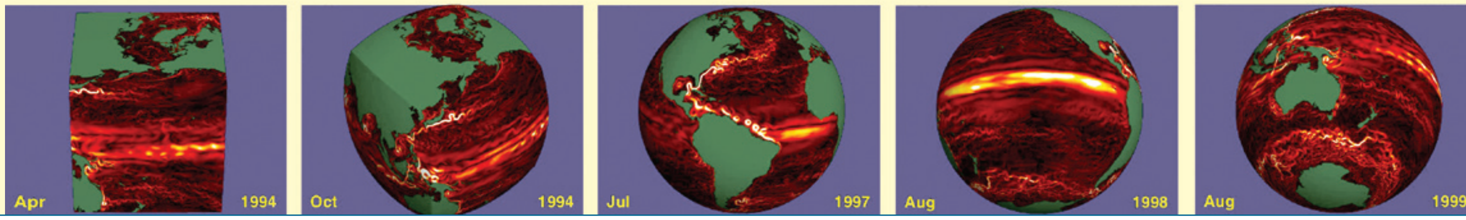
And finally, JPL's CloudSat, launched in April 2006, takes, for the first time, radar slices of clouds that allow us to determine the distribution of water and ice within them all the way down to the ground. Of all the things a climate model must do correctly, it's



clouds. And to make a long story short, the present models do not agree with cloud observations.

Oceans are important. If the atmosphere is weather, the oceans are climate. Ichiro Fukumori and others at JPL, along with sci-





This JPL/MIT/Scripps model of how water circulates in the global ocean has a resolution of one-sixth of a degree. For ease of computation, Earth is computed on a set of flat surfaces—the faces of a cube, which morphs into a sphere.

entists at MIT and the Scripps Institution of Oceanography, have made great progress with a global oceanic circulation model. In such a model, you don't want to use spherical coordinates—even though that's what we teach our students—because there is a nasty singularity at each pole, where meridians converge. This model solves the equations on the surface of a cube and maps the cube onto Earth's surface, avoiding the polar singularities. The colors in the pictures above are ocean-current speeds at 15 meters' depth. You can see the Gulf Stream, the Japan Current, many other features, and a lot of activity around Antarctica. There, the currents are constrained to go through the Drake Passage, the shallow, narrow strait between Argentina and Antarctica, causing the waters of the upper ocean to mix with the deep ocean. Much of the planet's upper-lower ocean mixing occurs there.

Meanwhile, a JPL-UCLA collaboration took several global-climate models that calculate conditions at widely spaced grid points, incorporated a finer grid covering central and southern California, and ran the models to see what detailed predictions each one makes about our region. The forecasted temperatures all go up, but there's quite a spread. Worse, the precipitation predictions are all over the place—not very useful if we want to know what's going to happen to California's water supply. Despite this, all the models predict that we're going to lose the snowpack in the Sierra Nevada. Much of California's water is stored there so, if true, the loss will be serious.

A PATH FORWARD

Countries like the U.S.—the largest energy user, both per capita and as a nation—can decrease energy use without much difference in our quality of life, if changes are gradual. As Nate Lewis said, the cheapest and cleanest power plant is one you don't have to build. (Amory Lovins once called these watts "negawatts.") With a sustained reduction in U.S. energy use of only 2 percent per year, or so, we may not even have to replace every older, less-efficient power plant as it reaches the end of its design life. This is eminently doable—Californians use only *one-half* as much electricity as the average American, in terms of kilowatt-hours per person per year, thanks in part to the work of Arthur Rosenfeld, an inspired physicist at Berkeley, and the support he was able to muster. This led to California setting efficiency standards for new buildings, as well as for appliances such as refrigerators, after the 1973–74 energy crisis. In 1972, Californians used about as many kilowatt-hours per person per year as the rest of the country. Our consumption has held steady at 1972 levels ever since, while the rest of the nation's has gone up. California's standard of living has not suffered as a consequence.

Next, we need to try carbon sequestration. However, if CO_2 is placed deep underground, it can leak. A leak rate of, say, 1 percent per year may sound pretty good. It isn't. At that rate, your first year's CO_2 will be back in the atmosphere in 100 years. Even so, we have to try to sequester, even if it doesn't work perfectly, because it will buy time. Carbon sequestration in the deep ocean is a possibility, as is reforestation, which we know works while forests are growing. Of course, before we consider planting new trees, we should stop cutting down the forests we already have.

So how *should* we produce the energy we need? Solar-thermal power-generation plants, like the Nevada Solar One facility in Boulder City, provide a good large-scale option. Such plants use computer-controlled mirror arrays to track the sun and focus its light to heat a liquid to nearly 400°C. This fluid is pumped through a heat exchanger to make steam that spins standard steam turbines that make electricity. Estimates indicate that with this technology in its current form, the southwestern United States and northern Mexico could meet the daytime power needs of the U.S., Canada, and Mexico. And we can do better—the Solana Generating Station being built near Gila Bend, Arizona, will be able to produce power for up to six hours after the sun goes down. The plant will have excess sunlight-collecting capacity that will be used to melt salt, which will be stored in giant thermos-like silos and circulated through the heat exchanger after sundown. Solana will crank out a peak of 280 megawatts, a quarter of a San Onofre unit, but will require three square miles of land. Real estate does become an issue at some point.

Nuclear power will play a role. Conventional nuclear plants need enriched uranium, because they run on uranium-235. U-235 is only 0.7 percent of the natural ore, which

Power production without smokestacks. The Nevada Solar One facility, left, has been running since June 2007. The third-largest facility of its kind in the world at the moment, it puts out 64 megawatts—enough to supply over 14,000 households. The Superphénix fast-breeder reactor, right, in Creys-Malville, Isère, France, was decommissioned in 1997.

The California High-Speed Train Project—a "bullet train" system proposed to link San Diego, Los Angeles, San Francisco, and Sacramento got its initial funding when voters approved Proposition 1A last November.

is mostly U-238. But a fast-neutron breeder reactor can use most of the U-238. It can also burn the "spent" fuel now stored as radioactive waste. France built such a plant, the Superphénix, in the 1970s. It was rated at 1.21 gigawatts, a little more than one of the San Onofre units. It used liquid sodium to cool the reactor core, which works fine as long as no sodium leaks into the heat exchanger's water side. You may remember from high-school chemistry that when water and sodium get together, exciting things happen—you get explosive hydrogen gas and lots of heat to ignite it. So even though nothing went wrong, the French decommissioned it. They're now building a new reactor that's safer *and* more efficient—and, ironically, uses CO_2 as its working fluid instead of steam.

Wind is cost-effective and wind farms on land may be able to meet about 10 percent of our power needs. JPL's Timothy Liu, Wenqing Tang, and Xiaosu Xie analyzed eight years of data from JPL's QuikSCAT satellite to estimate the wind power available over the oceans. They concluded that ocean wind farms, strategically located, could harvest up to 500 to 800 watts per square meter. (For comparison, average annual power available from sunlight at midlatitudes is some 250 watts per square meter.) We'd need to run power lines undersea, but we do a lot harder things routinely. However, one can only pump so much wind power into the grid, because wind is intermittent. Too large a fraction of it can make the grid unstable, unless one averages out its contribution through some sort of electrical storage system, which is expensive and difficult today at the required scale.

We could make big strides in transportation. Right now a plug-in hybrid, a converted Prius, can go up to 30 miles—more than the average American round-trip commute—on just the battery, and battery technologies are improving. But we need to start designing lightweight cars so that less energy is needed per mile traveled—as an aeronautics professor, I assure you that the typical payload fraction of today's cars is abysmal. For medium-length trips along transportation corridors, we need to expand rail transit. We'll probably keep jet planes for the long haul. We're not going to invent an electric commercial airplane any time soon.

As we transform our energy systems, we'll need to develop regional and global regulatory and pricing environments—cap-and-trade systems and carbon taxes, for example—that encourage a profitable, phased implementation with the least disruption. One could implement a carbon tax while cutting other taxes, for example, so that there is no net tax increase. However, any change leaves winners and losers, so we need to help losers to also be winners. That's not as difficult as it sounds, as the refrigerant engineer realized—the Montreal Protocol was *good* for the chemical industry.

THE ECONOMIC IMPERATIVE

This past May, former CIA director Jim Woolsey gave a talk at Caltech on energy. He pointed out that in 2003, the U.S. imported about 53 percent of the oil it consumed. Today it's about 60 percent. He said that we're borrowing $1.5 billion per *day* to pay for imported oil. Consumption and prices are now down because of the economy, but both will come back up as the economy recovers. The problem will not go away. It may take 30 to 40 years for Earth's radiative imbalance to catch up with us, but this financial imbalance is unsustainable and will catch up with us a lot sooner.

Conversely, transforming our energy system would provide a major economic stimulus, as the President-elect has noted. Besides creating jobs at home, the U.S. could sell efficient, reduced-carbon technology worldwide. America seems to need to reinvent itself every 20 to 25 years to stay competitive, as Tom Cwik, my friend and JPL's associate chief technologist, has noted. World War II pulled us out of the Great Depression. Then came Sputnik and the space race, followed by the Internet and the information-technology revolution. It's hard to imagine a better business plan for the nation than a significant increase in energy efficiency and a smart reduction in fossil-fuel use. With much of the world continuing to build old-style energy systems, little else would make the U.S. as competitive.

The year 2009 is a triple sesquicentennial. In 1859 Edwin Drake drilled the first commercial oil well, in Titusville, Pennsylvania; John Tyndall discovered that CO_2 absorbs in the infrared and noted the greenhouse-gas consequences; and Charles Darwin published *On the Origin of Species*. It'll be interesting to see how we evolve to solve this problem. e&s

Paul E. Dimotakis, the Northrop Professor of Aeronautics and professor of applied physics, is also the chief technologist for the Jet Propulsion Laboratory. In this latter role, he is in charge of thinking about technologies and seeing that they get developed to a point of readiness for when the Lab needs them in the future.

Dimotakis arrived at Caltech as a freshman in 1964, and has been here ever since, earning his BS (physics, '68), MS (nuclear engineering, '69), and PhD (applied physics, '73) before joining the faculty after a brief stint as a postdoc.

In his spare time, he is an avid sailor.

This article is based on a talk given at a Caltech Executive Forum on June 9, 2008 and was edited by Douglas L. Smith.

Remembrance of Crises Past

How did we get into this mess, and what should we be doing to prevent it from happening again? The past offers some lessons, say two economic historians.

"The one-dollar bill is the most ubiquitous piece of paper in America," writes currency collage artist Mark Wagner, who cuts up thousands of them to create pieces such as *I.O.U.* (left); his works are collected by dozens of institutions, including the Museum of Modern Art, the Walker Art Center, the Library of Congress, and the Smithsonian Institution. (Mark Wagner, *I.O.U.*, 2008, currency collage on panel; 12 x 16 inches.)

By Philip T. Hoffman and Jean-Laurent Rosenthal

THE PAST AS PROLOGUE

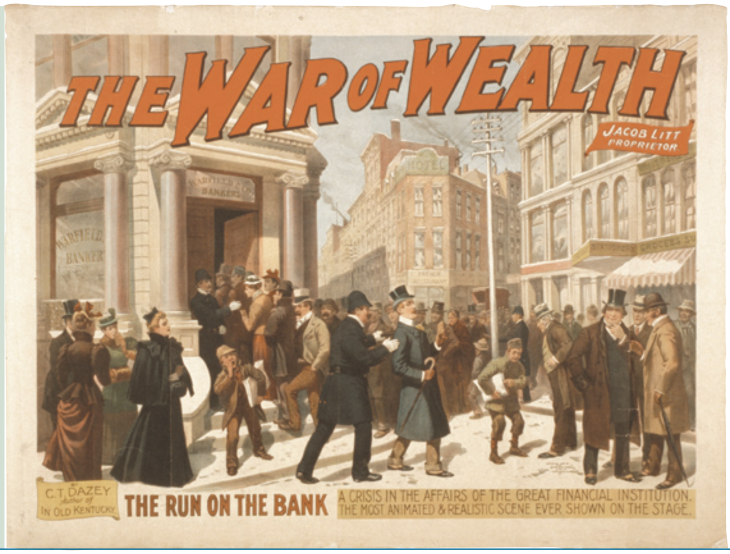
If we are to believe our financial leaders, the current crisis is, as a stunned Alan Greenspan told Congress, a "once in a century credit tsunami"—difficult to anticipate and completely unlike anything in the past. Or as former secretary of the treasury Robert Rubin explained in an interview with the *New York Times*, "Clearly, there were things wrong. But I don't know of anyone who foresaw a perfect storm, and that's what we've had here."

What strikes economic historians, though, is just how much this crisis resembles past financial collapses. Financial debacles often originate, as this one did, in a combination of an asset boom (in this case, rising housing prices) and a financial innovation (subprime mortgages and mortgage-backed securities such as bonds). Investors add this innovation to their portfolios, thus increasing its price by increasing the demand for it. The rapid price increase then convinces investors to buy more of the high-return and deceptively safe asset, and financial intermediaries strive to boost the supply. With swelling demand *and* supply, the quality of the asset soon begins to fall as the middlemen (the mortgage originators, asset brokers, and rating agencies) relax their standards for, say, creditworthiness. Meanwhile, investors borrow money to buy up even more of the new asset. At some point so much money is invested in dubious assets that the market inevitably breaks down, and if the collapse is large enough, the bad news cascades through the rest of the credit system and the economy as a whole. The beleaguered actors in the drama then rush for public assistance, saying, in effect, "Who knew?"

In fact, everybody knew—or should have known. Financial crises have repeatedly dotted the history of the United States (and the world), and they show no signs of going away. The U.S. was struck by a crisis originating in the real-estate sector as early as 1837. Real-estate prices had been soaring in the Midwest in the 1830s, and many states began bold plans to improve their road and canal systems. To fund these public works, they borrowed heavily in England in anticipation of higher real-estate taxes. When farm prices fell in 1837, the market for land crashed and 11 states defaulted on their bonds.

And a very close parallel to the current situation can be found in the mortgage crisis that battered the country in the 1890s. The origins of this crisis lay with the opening of the Great Plains to wheat farming. Settlers who wanted to improve or enlarge their farms could try to get credit from their local savings and loan associations, but these entities had limited funds. Furthermore, most households on the frontier were net borrowers, making interest rates relatively high. Western mortgages were thus attractive investments for eastern capitalists, and they created companies that hired loan agents on the Great Plains to find borrowers and make mortgage loans. The capitalists then issued bonds in Europe that were backed by the mortgages. Problems arose when a drought hit, and farmers throughout the Plains defaulted on their loans. The East Coast and European investors suffered the most, because competition among the mortgage companies had led them to drop the requirement that loan agents carefully check on the value of the borrowers' collateral. Rising real-estate prices, mortgage-backed securities, and competition leading to lax underwriting standards—sound familiar?

Our current predicament began with the spread of the now-infamous adjustable subprime mortgages, more than half of which are now in arrears. These mortgages were repackaged with other, sounder ones and resold at high prices based on a mathematical model whose fundamental flaws we'll discuss presently. Meanwhile, in the real world, decreasing or even eliminating the required down payment was allowing people with little savings (which frequently correlates with a shaky or nonexistent credit history) into the market. Consequently, more and more homes were being sold to buyers who could only meet their payments if housing values continued to rise while interest rates remained low. With benefit of hindsight it is clear that our real-estate boom depended on both home prices going up at least 10 percent per year for the foreseeable future, and nominal interest rates staying below 5 percent. It does not take a genius to see that these two conditions were unlikely to continue to hold for long. The resulting crash, however, is particularly severe, because the underlying market—for residential housing—involves a very large share of all the wealth in the country, and because the associated credit market dwarfs all the others. At a towering 14 trillion dollars, it is one-third larger than the national debt and accounts for 44 percent of all the outstand-



This poster for an 1895 melodrama depicts a scene familiar to 19th-century Americans—the United States experienced financial panics in 1819, 1837, 1857, 1873, and 1893.

ing private credit in the United States.

Similarly, in the 1930s, the Great Depression may have begun with a stock-market crash, but it wreaked such havoc in the housing and mortgage markets that the Federal Savings and Loan Insurance Corporation (FSLIC) and the Federal National Mortgage Association (Fannie Mae) were formed to ward off any future housing collapses. Since then, it may seem that we have escaped crises in mortgage markets, but that is not the case. The savings-and-loan crisis of the late 1980s as well as severe regional housing downturns (including one in the 1990s in Southern California) serve as reminders that residential real estate may be the oldest asset market on the planet, but it still contains an important element of risk.

When they formulated the complex mathematical models that allowed them to price mortgage-backed securities, financial firms ignored this history. The models are based upon the fundamental observation that what really matters is the overall trend in the value of your portfolio, not how the price of a given asset changes. In other words, it doesn't matter what each of your individual investments does—pork bellies may go up while soybean futures crash, but as long as the winners go up by more than the losers go down, you'll be fine. The key is diversification—don't put all your eggs in one basket, or all your money into pork bellies. In this case, the models presumed that since the bonds backed by subprime mortgages were really mostly backed by ordinary mortgages taken out by people with solid credit histories, the risk was sufficiently diversified that the bonds deserved very high ratings—which the brokers heartily encouraged, because it made the prices go up even further.

The only way to lose would be if *everything* went south at the same time, a phenomenon called undiversifiable risk. So the key issue, then, was how to measure that undiversifiable risk. To do this, financial firms relied upon data series that are merely a couple of decades long, or at best stretching back to World War II. It was as if the past were irrelevant. In a crisis, though, that can be a fatal mistake. During a crisis, as we all know today, virtually all private assets move in the same direction—down. There are therefore moments of enormous undiversifiable risk, but they are rare, at most occurring once every quarter century.

Rising real-estate prices, mortgage-backed securities, and competition leading to lax underwriting standards—sound familiar?

It may seem foolhardy to estimate the likelihood of such low-frequency events from such a short history—it's as if we only relied on the earthquake record of the Los Angeles basin over the last 25 years to calculate the likelihood of the Big One. But that is precisely what financial firms did. The 1985–2005 time series had another drawback as well: the housing boom began about when the dot-com bubble burst. The one acted as a cushion against the other, so homeowners who hadn't seriously overinvested in dot-coms didn't suffer *too* badly. After 2003 the housing and stock markets rose together, which was further good news. But the short span of data did not contain instances when the two markets dropped in tandem, as they have done recently, and so the financial firms overlooked this possibility.

Why were all the bright minds of Wall Street and all our financial regulators so blind to such a mistake? Once again, a look back provides an explanation. To begin with, Americans share a belief that technological change nullifies the past, and in particular makes the more distant past devoid of any useful lessons. Second, all of us who dabble in finance—even if only to save for retirement—yearn for investments that provide high returns without risk. Accepting the lessons of the past (and of modern financial theory) would force us all to realize that such portfolios are about as feasible as perpetual-motion machines. Third, regulators in the past few decades have faced tremendous political pressure not to intervene in financial markets. The real-estate boom was extremely popular. Republicans appreciated the expansion of the mortgage market as an element in constructing the "ownership society." Democrats promoted Fannie Mae and Freddie Mac's purchase of securities based on low-income mortgages as a way to extend access to credit to less-advantaged groups. Would-be homeowners favored relaxed lending standards because it allowed them to enter the housing market with less of a down payment. Those who were already homeowners gleefully reduced their retirement savings, since their houses were worth so much more. Not only that, they even practiced a kind of negative saving by using home-equity credit lines for big-ticket purchases, including fancy vacations—using their homes as ATMs, essentially. The construction industry could not but enjoy the fruits of high housing demand, as did real-estate agents, mortgage brokers, and local governments, which rely on property taxes for much of their budgets. And of course, the financial industry found the boom highly profitable. A message like "the higher the rise, the harder the fall" was clearly not welcome, but that, unfortunately, was the only message history offered.

SURVIVING LARGE LOSSES

For the past 12 months, our attention has been focused on attenuating the short-term impact of the crisis. The U.S. and other governments have enacted large-scale stimulus packages, spent billions shoring up shaky balance sheets, and pledged billions more to reassure individuals that their bank deposits are safe. These acts have transformed the financial landscape. The few surviving large independent investment banks have morphed into bank holding companies in order to enjoy the benefits of backing by the Federal Reserve. In the commercial banking world, intervention to salvage institutions battered by large capital losses has created four truly national banks, which hold a shockingly large share of all deposits. Such concentration would have been unthinkable a mere decade ago, or even a few months ago. To be sure, the creation of large national banks is a good thing for many reasons, among which are that they can give consumers access to ATMs across the country, and that they take advantage of economies of scale in the information technologies that underpin the banking business today. Nonetheless, the absorption of Washington Mutual by J. P. Morgan Chase and of Wachovia by Wells Fargo was driven by expediency, rather than by careful planning for the long-term health of the American financial system. And as the recent near-collapse of Citigroup demonstrates, even big banks can have huge problems if they are not properly supervised.

These structural changes will have consequences long after the flow of government money comes to a halt. What more—if anything—should be done? An understanding of the long-term evolution of financial markets suggests two fundamental rules that should guide further change: the mortgage problem must be addressed at the level of the homeowner, and partial regulation is bad regulation.

The heart of the current financial crisis is that some homeowners cannot afford the payments they have contracted to make, while others find defaulting attractive because the value of their homes has dropped well below what they owe. As mortgage losses mount, banks have to reduce their ability to make new loans—most banks have requirements that limit their lending to some percentage of the firm's capital. The decline in bank stocks has aggravated the problem, forcing banks to hold on to whatever income they earn simply to meet prudent balance-sheet requirements. Given that banks have lost about 40 percent of their overall value, it is not surprising that credit has been tight.

One can imagine two solutions to this problem. First, if banks were forced to hold higher reserves to cover future losses on risky loans or on investments in exotic derivative contracts, future crises would be less severe, because banks would be better prepared for them. Such a requirement would also make nonstandard investments more costly, because they would require idling more capital to cover any potential losses. Banks would therefore have less incentive to load up on risky bets. However, there is a problem—in a world of complicated asset portfolios, government regulators are at a very serious disadvantage in deciding what a prudent reserve ought to be. If the regulators are too conservative, they will stifle innovation; if they are too lax, they invite crises. And in the absence of long historical data series for guidance, the task of creating portfolio rules may well smack of reading tea leaves. (One could, of course, hire armies of economic historians to put together the necessary data series, but that would take years.)

The alternative, which we favor, is to focus directly on mortgages, and require that buyers make a minimum down payment and demonstrate that they have enough income to service their loan. Such requirements are not new, but they have never had the force of law. In the 19th century, it was standard to limit mortgages to half the value of the property. With such a high down payment, an income requirement was unimportant. When the last real-estate bubble burst in Los Angeles in the 1990s, it was difficult to get a loan with less than a 20 percent down payment. Whether the minimum down payment now should be 20, 15, or 10 percent is something that can be debated. If we choose to impose low down payments, we should tack on income verification standards, as is done with conventional mortgages. We should also make sure that homeowners cannot take out home equity loans that would push them beyond a prudent loan-to-value ratio. A higher down payment requirement will, of course, freeze some people out of the market and thus reduce the demand for owner-occupied housing, particularly expensive housing. But it will also cut the likelihood of crises, by insulating the financial system from defaults triggered by small price declines. In any case, it is clear that loans with no down payment are recipes for disaster. With down-payment and income-verification rules in place, homeowners might be putting in fewer granite countertops, but they wouldn't be fretting about their pensions.

Rules about income and down payments are easy to write, and easy to enforce. Our long-standing, county-level mortgage-registration system already keeps track of all loans backed by a particular piece of real estate, and we have adequate, if not perfect, means of assessing both housing values and income. Of course, the real-estate and banking sectors may not like having such rules imposed by legislation. They may argue that they are moving in this

This 1910 cartoon by Frank A. Nankivell for *Puck* magazine shows John Pierpont Morgan with his right arm encircling New York City's financial district while his left reaches for a child's piggy bank. The caption across the bottom reads, "The Central Bank—Why should Uncle Sam establish one, when Uncle Pierpont is already on the job?"

direction on their own. But one should bear in mind that industry standards of this sort tend to disappear in boom times, leading inexorably to the next crisis. Now is the time to implement such safeguards legislatively, while the chastened banking and real-estate industries' traditional opposition to public regulation is stilled by their desperate need for government largesse.

PARTIAL REGULATION IS BAD REGULATION

More broadly, the Federal Reserve should be given authority over all financial actors—not just commercial banks, and not just big entities, but *all* financial firms. Currently the Fed has a very specific set of mandates that give it clear authority over commercial banks, but little formal power over investment banks or insurance companies, and no hold at all over hedge funds. While its powers over investment banks and insurance companies have expanded in the current crisis, the financial sector has balked at giving it authority over hedge funds.

The Fed's shackles have historical roots. The Federal Reserve system was created in response to the Panic of 1907, when the discovery of stock-market shenanigans led to runs on many commercial banks. The United States had no central bank, so a group of private financiers led by J. P. Morgan wound up pledging tens of millions of dollars of their own money to stabilize the system. Yet even after this crisis the idea of a central bank was regarded with deep suspicion in many quarters, so in a compromise the Federal Reserve was created to monitor and provide liquidity to commercial banks across the U.S., while ignoring investment banks and allowing states to maintain their authority over other businesses, such as savings and loans and insurance companies.

Although the Federal Reserve's role has grown in recent decades, as banks have become truly national for the first time in our history, its purview is still limited by other federal agencies such as the Federal Deposit Insurance Corporation and the Securities and Exchange Commission, and its ability to regulate many financial actors remains at best indirect. Since it has no authority over hedge funds or insurance companies, in theory it has no obligation to help them out when they get into trouble. The founding philosophy was that if such a firm should fail, tough luck—that's the investors' problem. However, the current crisis has taught us that we don't believe in tough luck. The argument will no doubt be made that giving the Fed such oversight will stifle innovation, and it may well be true that innovation in financial markets might be slowed by more stringent regulation. On the other hand, for political and practical reasons the Fed cannot let big firms that are independent of its authority fail. Implicitly, these firms are getting the benefits of possible Fed assistance in the future. That can make them take undue risks, leaving taxpayers with the bill. They therefore have to submit to regulation by the Fed.

Leaving aside the political pressures that can be exerted to have the Fed save a huge hedge fund such as Long Term Capital Management, or an insurance company such as AIG, there are also practical reasons for allowing the Fed to take on such rescue operations. The first is that these institutions are enmeshed in a web of contracts with the firms that the Fed regulates. As the failure of Lehman Brothers shows, the collapse of one of these firms can have dramatic effects on the rest of the financial system; letting AIG fail would have led to even worse consequences. The problem is not simply that some firms are too big to fail. Rather, it is that if any segment of the financial market gets out of control, it can send shock waves throughout the system, even when the firms in crisis are small. The subprime mortgage market, after all, was only about 10 percent of the value of all mortgages and only 20 percent of the new mortgages in 2006, but its demise has triggered real estate's worse crisis in 80 years. Thus no big firm can stand outside the Fed's purview, and no large segment of the financial market can escape its authority.

If we do let one part of the market escape the Fed's regulation, all sorts of problems can arise. Consider how banks reacted to competition from unregulated hedge funds. As the hedge funds racked up large returns with their new financial techniques, traditional banks faced a drain of clients and talent that migrated to the innovators. The banks lobbied for some mechanism that would stanch the flow, and a solution was found by allowing them to hold much of their high-risk activities in Special Investment Vehicles, essentially dummy corporations, so as to keep them off their books—and thus outside the scope of regulators, and beyond the ken of most investors. When the subprime problem surfaced, some of the banks had to bring this activity back onto their balance sheets, shocking investors with huge losses. Had the playing field been level, no such sleight of hand would have occurred.

IT'S HARD TO MAKE PREDICTIONS, ESPECIALLY ABOUT THE FUTURE

Requiring down payments on mortgages and giving the Federal Reserve authority over the entire financial system will reduce the damage crises do, but these two measures will not eliminate crises altogether.

Financial markets have the very difficult task of directing resources towards high-return investments while diversifying risk. Without a crystal ball, investors have to guess about the future, and sometimes they will be wrong.

Nevertheless, our two rules should be adopted now, for we know that this will not be the last crisis to hit, and for the moment we have a coalition that is eager for reform. Now is the time to design financial markets to be robust—not just in regard to the history of the last couple of decades, but to a very broad set of events. We should assess risks not just with short sets of recent data but with evidence from the past.

These difficult times are also ushering in complex transformations in our households and in our international relationships. The days when Americans could believe that long-run prosperity was compatible with a personal savings rate near zero are now over. From the mid-1980s to the present, we enjoyed unprecedented run-ups in stock prices, and then in housing values, that created personal wealth with little or no effort on our part. We should not expect such good luck in the future. Given the increasingly large fraction of the population that is elderly, an increase in Social Security benefits is unlikely. If Americans want to retire comfortably, they will have to save.

In part because this is an election year, the crisis has been managed largely as a domestic problem. However, it is international, and will continue to affect the whole world. A latent fuel to the credit boom that moved us to this crisis was the world's willingness to lend us money, including the billions of dollars that China had amassed in foreign-exchange reserves and the large stakes that many foreign banks had taken in our mortgage market. While increasing our savings rates may wean us from a habit of foreign borrowing that is even more dangerous than our dependence on foreign oil, it will not change the fact that the financial market is global. Venice, Paris, and London have all been the centers of the financial world, only to be supplanted after various crises rocked them. If we want New York to remain the world's preeminent financial center, we must insure that our financial house is in order. e&s

Philip T. Hoffman, an Axline Professor of Business Economics and professor of history, earned his PhD from Yale in 1979, and arrived at Caltech as a lecturer in 1980. His highly collaborative research applies the tools of the social sciences to track long-term historical changes in politics, societies, and their economies to try to understand why some countries grow rich, while others remain mired in abject poverty. This includes studying the evolution of financial institutions such as stock exchanges and their effect on economic growth, and also such broader questions as why the West managed to conquer the rest of the world. (His December 2006 Watson lecture on this subject is available on the Caltech Streaming Theater website.)

Jean-Laurent Rosenthal is the other Axline Professor of Business Economics and the Executive Officer for the Social Sciences. He earned his PhD with Hoffman in 1988, and his research also focuses on the interaction between institutions and economic growth. He, Hoffman, and Gilles Postel-Vinay of the Laboratory of Applied Economics at the Institut National de la Recherche Agronomique (the National Institute for Agricultural Research) in Paris, France, have studied the growth of mortgage markets from the 17th to the end of the 19th century in France. Rosenthal, Thomas Piketty of the Paris School of Economics, and Postel-Vinay are working on a large-scale data-collection project to document the evolution of the distribution of wealth in France from 1800 to the present.

Hoffman and Rosenthal's most recent book (with Postel-Vinay) is **Surviving Large Losses: Financial Crises, the Middle Class, and the Development of Capital Markets** ***(Harvard University Press, 2007). Previous books include*** **Finance, Intermediaries, and Economic Development,** ***which they edited with Stanley L. Engerman of the department of economics at the University of Rochester in Rochester, New York, and the late Kenneth L. Sokoloff, a professor of economics at UCLA (Cambridge University Press, 2003), and*** **Priceless Markets: The Political Economy of Credit in Paris, 1660–1870,** ***also written with Postel-Vinay (University of Chicago Press, 2000).***

This article was edited by Douglas L. Smith.

Hoffman (left) and Rosenthal (right).

When the Big One Hits

More than 1,100 kilometers long, the San Andreas fault separates the Pacific and North American tectonic plates. The fault marches straight down this photo of the Carrizo Plain National Monument, which is about 150 kilometers north of Los Angeles. Because the plain is an arid environment, there isn't much erosion, and the fault scarp remains visible.

Seismologists say the Big One could strike any day. To better prepare for a potential catastrophe, researchers are simulating how buildings respond to earthquakes and helping to conduct the biggest earthquake drill ever.

On November 13, 2008, at 10 a.m., the San Andreas fault jolted Bombay Beach, a small town on the shores of the Salton Sea, 100 kilometers southeast of Palm Springs. In a split second, the two sides of the fault slid 13 meters. Like a zipper unzipping, the rupture shot 300 kilometers northwestward along the fault at more than three kilometers per second, sending seismic ripples across Southern California. The 7.8-magnitude earthquake rocked the Los Angeles metropolitan area, shaking the basin for nearly a minute. Buildings collapsed and dozens of city blocks went up in flames. With water lines broken, there wasn't enough water to fight the conflagration. 1,800 people died and 50,000 were injured. The quake caused more than $200 billion in damage. Strong

The Great Southern California Shake Out!!

By Marcus Y. Woo

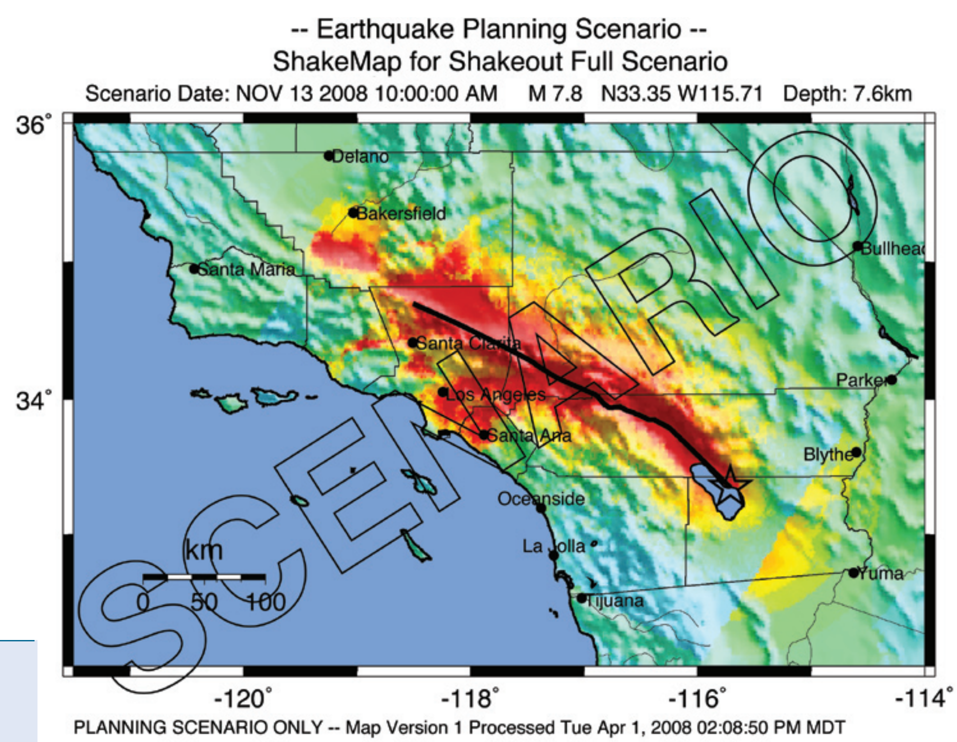
aftershocks—some bigger than the last big quake in the region, the 6.7-magnitude Northridge quake in 1994 that killed 57 people—struck often and hard. The catastrophe would affect businesses and lives for years to come.

Fortunately, of course, this never really happened. The scenario described above was the plot line of the Great Southern California ShakeOut, the biggest and most comprehensive earthquake drill ever. The ShakeOut scenario was a strong quake, but neither a worst-case scenario nor an improbable one. In fact, there's a 99 percent chance an earthquake of 6.7 magnitude or greater will hit California in the next 30 years, according to a recent report by the United States Geological Survey.

Chances are, that quake will be on the southern portion of the San Andreas fault, where the Pacific Plate slides along the North American Plate at the blistering pace of a few centimeters per year. Although the word "plate" may connote breakable dinnerware, tectonic plates are not entirely rigid. While the rest of the Pacific Plate gently moves northward, friction keeps the edge along the fault locked to the North American side. Over decades, the strain builds. Eventually the fault ruptures and the two plates slip, covering in one catastrophic moment the distance traveled by the rest of the plate in centuries. Although the fault runs along the north side of the San Gabriel Mountains—40 kilometers from Los Angeles at its closest approach—the reverberations are felt for hundreds of miles. Seismologists think that a big quake on the southern San Andreas happens as frequently as every couple hundred years or so, and the last massive one—a 7.9 temblor known as the Fort Tejon quake—hit on January 9, 1857. Although seismologists can't predict earthquakes—they emphasize that the Great ShakeOut was not a prediction but a "what if" scenario—they warn that California is due for the Big One.

The ShakeOut, however, was more than a glorified version of a duck-and-cover drill, familiar these days in earthquake country. The goal was to prepare Southern California for the next big earthquake with the most realistic scenario possible, one based on the best science available. The drill relied on detailed computer simulations, and from those simulations, more than 300 experts derived specific emergency situations such as damaged water, power, oil, and railroad lines, widespread fires, and broken telecommunication links. They quantified the impact on the infrastructure, the economy, and individual lives.

As some seismologists like to say, "Earthquakes don't kill people. Buildings kill people." Because Southern California was sparsely populated in 1857 and tall buildings were still a century away, the Fort Tejon quake claimed only two lives. But today, hundreds of buildings tens of stories high scatter the region, and the ability of these structures to hold up to earthquakes will be



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

This ShakeMap shows the extent of the simulated earthquake's shaking. Although scientists can't predict when and how future earthquakes will strike, they can assign a size and location to a hypothetical earthquake and predict its effects.

Nearly 70,000 people died in Sichuan, and thousands of them were children who were crushed under poorly constructed schools. "When you lose children," Krishnan remarks, "you lose a whole generation of people."

the difference between life and death. In fact, half of the fatalities from the ShakeOut scenario were from collapsing buildings.

Assistant Professor of Civil Engineering and Geophysics Swaminathan Krishnan (PhD '03) shakes buildings on a computer to see whether they will survive. For his PhD thesis, he wrote software that models how every element of a building would respond to jostling. A couple of years ago, he started collaborating with Jeroen Tromp of Princeton, who was then Caltech's McMillan Professor of Geophysics and director of the Seismological Laboratory. Tromp's area of expertise was simulating earthquakes with computers, perfectly meshing with Krishnan's work. Together, they created the first "end-to-end" simulations, modeling a complete scenario from the "bottom end" of a seismic rupture and regionwide earthquake, to the "top end" of an individual shaking building. According to Tromp, their collaboration marked the first time seismologists had joined forces with civil engineers to analyze how structures resist—or succumb to—earthquakes.

Building codes in California are rewritten periodically so that they're as up to date as possible, but because data detailing buildings' performance in large earthquakes are hard to come by, simulations are crucial in determining whether the codes are up to snuff. As the magnitude-7.9 Sichuan quake last May tragically illustrated, collapsing buildings can be catastrophic. Nearly 70,000 people died in Sichuan, and thousands of them were children who were crushed under poorly constructed schools. "When you lose children," Krishnan remarks, "you lose a whole generation of people." Sichuan was a sobering reminder of an earthquake's devastation. As an engineer, Krishnan says he relishes the intellectual challenge of calculating structural responses to earthquakes. But ultimately, his goal is to save lives.

TIME TO SHAKE THINGS UP

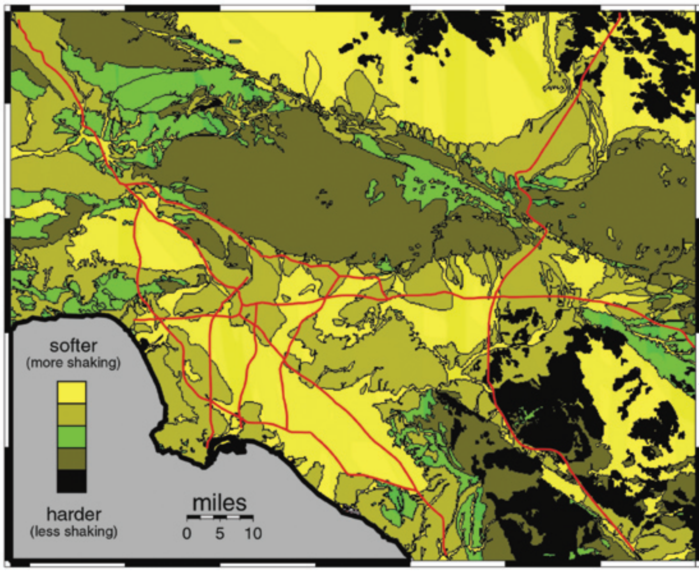
Krishnan and Tromp's initial study looked at that 1857 earthquake, one of the biggest in U.S. history. Although most of the damage centered on the region's most populated area—Fort Tejon, an army outpost about 120 kilometers north of Los Angeles—shaking was felt throughout the Los Angeles basin and as far away as Las Vegas. The *Los Angeles Star* reported that the Los Angeles River sloshed back and forth, Krishnan says, and the researchers deduced that for such a large body of water to slosh so much, the shaking must have been pretty intense and must have lasted from one to two minutes—a long time compared with the Northridge quake, which shook for only 10 to 20 seconds.

The sloshing also implied that the 1857 quake had seismic waves with relatively long periods, ranging from two to eight seconds. These long-period motions are especially worrisome because they target tall buildings. Buildings are like pendulums—a longer pendulum swings more slowly than a shorter one. When the seismic wave period matches the building's natural resonant frequency, it will sway—and possibly break and collapse. (For example, the nine-story Millikan Library in the center of campus is sensitive to a period of 0.85 seconds.) The Fort Tejon earthquake would have shaken buildings in the range of 15 to 20 stories the most, had they existed. Buildings of a few stories would have been largely undisturbed, much like small leaves gently riding wind-driven swells in a lake. Damage was pretty severe where there was anything to damage—part of the Mission San Buenaventura's tower in Ventura collapsed, for example. Today, with hundreds of buildings 15 or more stories high scattered across the region, long-period motion could have devastating consequences.

We can't escape low-frequency rocking—it's a characteristic of our geology. Los Angeles sits in sedimentary basins that formed 15 million years ago after the surrounding mountains rose. Over time, the sea and rivers carried sediments into the basins, creating a thick, soft layer 10 kilometers deep on which Los Angeles and its suburbs have been built. During an earthquake, the seismic waves bounce back and forth between the hard walls of the surrounding mountains, like water sloshing in a bathtub.

Tromp's work builds on dramatic advances in computer hardware and numerical techniques over the past decade. The earthquake simulation starts with what's called a source model, which details where the rupture started, how fast it moved, and how far it went. There weren't any seismo-

The Sichuan earthquake in May 2008 destroyed many schools, including this middle school in the town of Yingxiu.



This map of the Los Angeles region shows the softness of near-surface rocks and sediments. Data for image courtesy of Chris Wills, California Division of Mines and Geology.

graphs in 1857, so the researchers, including Krishnan, Tromp, Chen Ji (PhD '02) of UC Santa Barbara, and Dimitri Komatitsch of the University of Pau in France, turned to measurements of the 7.9-magnitude earthquake in 2002 that shook Denali in Alaska. The Denali fault system is similar to that of the San Andreas, and would serve as a reliable proxy. The investigators made a source model and incorporated it into the key component of an accurate earthquake simulation: a three-dimensional model of Southern California's geology, created to determine how fast different kinds of seismic waves would propagate.

This earth model, as it's called, uses data from actual earthquakes. Just as a gentle tap helps you find the juiciest watermelon, seismic waves traveling through the ground betray the earth's hidden structure. Even the smallest quake provides valuable information, and the Southern California Seismic Network (SCSN) constantly monitors the earth's rumbles and murmurs. Run by Caltech and the USGS, the network consists of 350 sensors scattered from the U.S.-Mexico border through San Luis Obispo and Big Pine. Analyzing a wave's arrival times at each of the SCSN's far-flung stations reveals occurrences such as subtle changes in density, which governs wave speed.

Although the network is one of the largest and most sophisticated in the world, it's still limited. Sensors don't blanket every square meter of the region, constraining the model's resolution. Short-period wavelengths are shorter than the size of the mesh, so researchers can only reliably simulate long-period shaking—waves with periods greater than about two seconds.

Short-period shaking quickly dies out as the waves propagate away from the fault, so neglecting them is fine when simulating bigger earthquakes, such as the Fort Tejon quake or the ShakeOut scenario, in which long-period motions dominate a large swath of land. But close to the fault rupture, the short-period trembling is powerful—and, as we've seen, causes more damage to smaller buildings, such as homes. Southern California has plenty of faults that lie right underneath our houses. One is the Newport-Inglewood fault, which stretches 75 kilometers from Culver City to Newport Beach, and last ruptured in the 6.3-magnitude Long Beach quake in 1933. Another is the Sierra Madre fault that lies north of Pasadena. Near Caltech are the Hollywood Hills fault, Eagle Rock fault, and the Raymond fault, which goes from San Marino to Arcadia and passes about two kilometers south of the Caltech Seismology Lab. Prudence would require simulating short-period motions as well, meaning a denser seismic network is needed to increase the earth model's resolution. But conventional seismic stations are expensive and require dedicated data lines to the central processing system. So Caltech seismologists are developing a cheaper, portable sensor network that can be used not only in Los Angeles, but also in places with weaker infrastructure such as Mexico, Peru, and China (see box next page).

To ensure their simulations were accurate, the researchers used the Northridge quake to test their simulation. Krishnan's team took half of the seismograph recordings to reconstruct the rupture and develop a source model. They then recreated the Northridge quake and compared the synthetic waves with the other half of the data, and indeed, the simulations matched well.

Then, armed with the Denali source model, the earth model, and 200 processors, the researchers simulated two earthquakes. Both were of magnitude 7.9 and ruptured 290 kilometers of the San Andreas. The first, however, was similar to the 1857 one, in which the rupture started at Parkfield in central California and went southward toward Los Angeles. In the second, the rupture started just north of Los Angeles, and continued northward to Parkfield. In the first case, the seismic energy was aimed at the heart of the city; in the second, it was flipped around. So how would this change affect our buildings?

A New Seismic Network

From left to right: Simulated seismic waves from the Chino Hills earthquake that hit on July 29, 2008. The wave field as sampled with the current network density shows little coherence. The predicted field sampled with 1,000 stations, however, shows clear wavefronts.

A new seismic network may be coming soon to a computer near you. A group of Caltech seismologists led by Robert Clayton, professor of geophysics and acting director of the Seismological Laboratory; Thomas Heaton, professor of engineering seismology and director of the Earthquake Engineering Research Laboratory; Mani Chandy, Ramo Professor and professor of computer science; and Monica Kohler, a visiting associate in civil engineering, are developing a new, low-cost, portable earthquake-measuring device that may help mitigate the impacts of catastrophic quakes—and possibly save lives.

The quarter-sized gadget, which attaches to computers through a USB port, would be part of a global network of seismic sensors that provides real-time data on the level of shaking after an earthquake. For example, the instrument could tell people immediately whether it's safe to go back inside their homes or schools after a quake. Additionally, units close to the epicenter can provide a warning to more distant sites a few seconds before a coming temblor.

Because they're cheap and small, the new sensors can also be easily deployed to bolster the Southern California Seismic Network (SCSN), the 350-unit system now scattered across the Southland. An improved, denser network—the target being a total of one thousand units—will allow scientists to deepen their understanding of earthquakes and build more precise earth models that are crucial for seismic simulations.

Run by Caltech and the USGS, the SCSN is not just an academic enterprise. It has proven invaluable for helping direct emergency response to earthquakes. For example, the SCSN produces "ShakeMaps" that detail where and how much the ground shook. Once computers in the Seismological Laboratory detect an earthquake—which can be as small as 2.5 in magnitude—they automatically produce a map and post it online, mere minutes after the quake. (To see ShakeMaps, go to http://earthquake.usgs.gov/eqcenter/shakemap/).

The current network's seismometers are connected by dedicated links to Caltech's Seismological Laboratory and are high-precision sensors, but they are difficult to install and maintain, and cost $100,000 each. The USB device costs only tens of dollars and relies on its host computer for power, communication, and some processing capability. (The researchers are also exploring the use of a larger, self-contained unit the size of a lunch pail. This $3,000 device, which only needs a power supply and wireless Internet, is designed to be placed in secure environments such as fire stations.)

The tiny unit, which employs the same technology as a car's airbag triggering mechanism, is less sensitive than the $100,000 seismometer, but its price and portability is unparalleled. In quiet times, the sensors phone home once a day, so scientists can keep tabs on the network. If an earthquake strikes, the unit logs in to report the peak magnitude, duration, and frequency of the shaking.

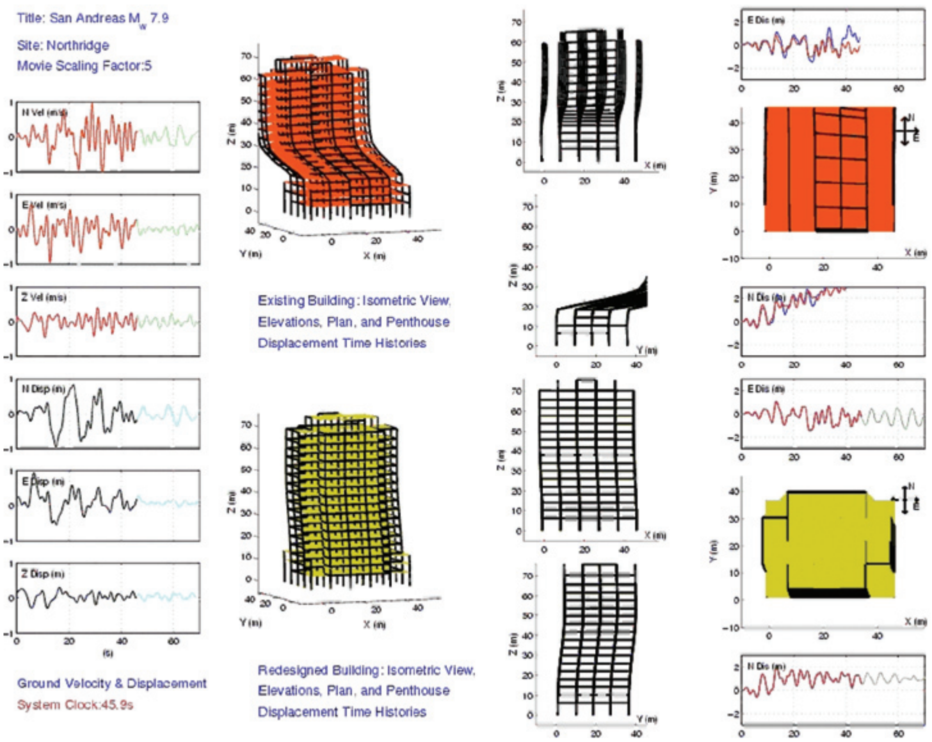
The researchers are starting a two-year pilot program to place the smaller units in 28 schools around Pasadena. The ultimate goal is to deploy a million of these gadgets around the world—in particular, in places such as Mexico, China, and Peru. Those countries lack the infrastructure to easily build a seismic network. But, with Internet cafés everywhere, those places are easily reached via cyberspace and are perfect for the new sensors, Clayton says.

BROKEN BUILDINGS

The 1994 Northridge earthquake caused more than $40 billion in damage and revealed the weaknesses of so-called steel-moment-frame buildings. Moment frames consist of a grid of beams and columns welded together, and are designed to resist the horizontal motion caused by rocking ground. Engineers thought the connections that joined the beams and columns were ductile, stretchy enough to resist being pulled apart. But Northridge showed that this wasn't the case. Cracks were found along the welds, which were more brittle than engineers thought. Also, the welding process itself inadvertently created points susceptible to stress, making the problem worse. Furthermore, many of the damaged buildings were built before 1976, when less was known about structural resistance to earthquakes. The lessons learned from Northridge led to updated building codes in 1997. But Los Angeles hasn't had a big quake since then—so are the new specifications adequate?

To find out, Krishnan's team modeled a building that was damaged in the Northridge quake—an 18-story steel structure built in 1984 on Canoga Avenue in the Woodland Hills district of the San Fernando Valley. This building has been the subject of numerous studies and is relatively well understood. The researchers placed 636 identical copies of that building about 3.5 kilometers apart on a grid covering the Los Angeles metropolitan area from Huntington Beach to Simi Valley. They then shook each building with the

This snapshot of a movie shows Krishnan's simulation of a building's response to the Northridge earthquake. The existing structure designed with pre-1997 building codes is on the top half. The redesigned building with updated codes is on the bottom. The graphs in the far-right column show how much the building is twisted. The blue lines represent the displacement of one corner of the roof, and the red lines depict the opposite corner. Their divergence represents the twisting motion. There is so much twisting that the pre-1997 building collapses.



specific seismic waves that the earthquake simulations dictated for that particular location, and calculated how every beam, column, and joint of the building would move. The researchers made two grids—one with the existing buildings designed according to 1982 codes, and one with a redesigned buildings with the updated codes.

The simulations showed that, indeed, the new buildings fared better. In the first earthquake—the one headed toward Los Angeles—many of the connections fractured in the pre-Northridge designs. In the San Fernando Valley, more than 25 percent of them failed in each building. In areas such as West Los Angeles, Santa Monica, Inglewood, Alhambra, Anaheim, and Seal Beach, 20 percent of the connections fractured. In downtown Los Angeles and Beverly Hills, the fracture fraction was 10 percent.

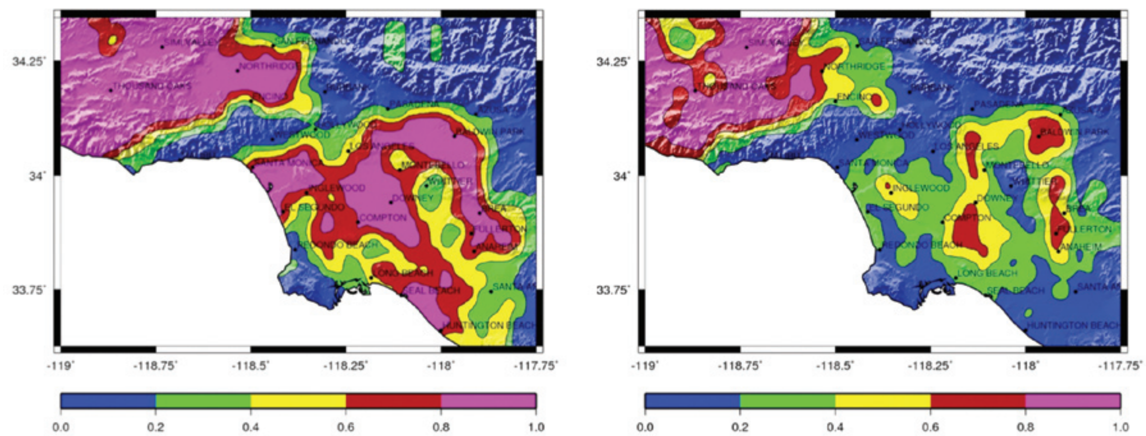
While the percentage of fractured connections is telling, the key measurement is the interstory drift ratio (IDR), which is defined as the difference in displacement between the top and bottom of a story, divided by the story's height. The higher the value, the more the ceiling is offset from the floor, and the more the building is bent out of shape. The Federal Emergency Management Agency (FEMA) sets three levels of damage based on IDR values. Different from the colored-tag system used for assessing buildings after a post-earthquake inspection, the IDR-based levels are used for more quantitative analyses. The category with the least amount of damage is called "immediate occupancy," defined as having IDR values of 0.007 or lower. These buildings may need some minor repairs, but as the name implies, they are safe to live and work in. Buildings with IDRs up to 0.025 are labeled "life safe," meaning they've suffered significant damage but aren't about to collapse. FEMA considers buildings with IDRs up to 0.05 at risk of collapse—these buildings may still be upright, but they're on the verge of coming down. If the IDR is greater than 0.05, the building is literally bent out of shape, and would likely be given red tags after a post-earthquake inspection, meaning the building's off-limits.

In the simulations, the highest IDR values in buildings were way above FEMA's collapse prevention level of 0.05—they were more than 0.1—in the San Fernando Valley, Santa Monica, and the areas surrounding Baldwin Park, West Los Angeles, Norwalk, and Seal Beach. Tall buildings in these areas would most likely become rubble. In downtown Los Angeles and Beverly Hills, the IDR values hit 0.05. Furthermore, the earthquake caused the most damage to the lower and middle thirds of the buildings, increasing the risk of the structures pancaking on themselves.

The new buildings fared better, as you would hope. None of the ones in the Los Angeles basin had IDRs of greater than 0.05. Although these buildings would most likely be closed down because of permanent tilts, they probably won't fall on people. Still, simulations struck San Fernando Valley hard, causing most buildings there to have IDRs 0.1 or higher. But this doesn't mean that the San Fernando Valley is doomed. The damage depends strongly on the specific earthquake, as shown dramatically in the second simulation when the rupture was flipped around and traveled from south to north.

This second scenario produced far less ground shaking throughout the region. In the case of the old buildings, the San Fernando Valley saw only 3 to 7 percent of its connections fracture. In Santa Monica and El Segundo, about 4 to 5 percent were fractured. There was minimal fracturing elsewhere.

The lessons learned from Northridge led to updated building codes in 1997. But Los Angeles hasn't had a big quake since then—so are the new specifications adequate?



Krishnan's and Muto's estimated costs of damaged and collapsed buildings from the ShakeOut. Buildings at places with a value of 1.0 (magenta) will have to be replaced. A value of 0.1 (blue) means the damage will be 10 percent of the replacement cost (estimated to be $72 million). The map on the left is based on the pre-1997 building codes. The one on the right is based on the updated designs.

The highest IDR values were 0.03—heavily damaged but not in danger of collapse—in the San Fernando Valley, Santa Monica, El Segundo, and Baldwin Park. The new buildings were just slightly better, experiencing IDRs of at most 0.03. Most were around 0.01. "If scenario one occurs, it may collapse some of our buildings," Krishnan says. "But if scenario two occurs, it may not be all that bad, so let's pray for scenario two."

Of course, this analysis was based on just two specific building designs and two specific earthquake scenarios, and extracting broader implications is difficult. "Should we do anything about issues that this study raises?" Krishnan says. "Well, should you put money in the stock market? Should you put it in mutual funds or high-risk stocks? It's the same question. It depends on the risk-averseness of society at large." At the very least, this work shows that reliable simulations combining seismology and civil engineering are possible, a prelude to more sophisticated studies in the future. One immediate application could be to test the safety of an important new building—a new hospital in downtown Los Angeles, for instance.

Krishnan's group is now looking at the collapse susceptibility of other designs, such as so-called braced-frame buildings, which feature diagonal struts for extra support. Ultimately, he hopes to run simulations of many different structures in various earthquake scenarios and be able to provide city planners and officials with quantified estimates of damage and risk for any building in Los Angeles.

The researchers also want to make their simulations even more realistic by including the interactions between the building and the soil it sits on. Earthquakes loosen the top layer of soil, which changes the behavior of the building, adding another level of complexity. Geophysicist Tromp wants to push the collaboration between engineers and seismologists to tackle these problems. "This is where the next frontier lies," he says.

THE POTENTIAL FOR CATASTROPHE

But analyzing the impacts of earthquakes doesn't stop at crooked buildings. These "end-to-end" simulations run from seismic source to shaken structures. But the true "end" of the analysis could be pushed farther—examining not only physical damage, but also economic loss. So Krishnan, research scientist Matthew Muto (MS '01, PhD '07); James Beck (PhD '79), professor of engineering and applied science; and Judith Mitrani-Reiser (PhD '07) of Johns Hopkins have taken the first steps to derive the probabilistic costs of repairing—or replacing—the buildings that were damaged in the simulations.

First, they looked at a previous study done on 12 structures damaged during the 1995 earthquake in Kobe, Japan. (At a magnitude of 6.9, Kobe was roughly comparable to Northridge). Using this data, they figured out the probability that the entire building would need to be replaced or repaired, and how much that would cost. They used the IDR values as a measure of how likely it was that the buildings would be damaged, with higher values meaning a greater chance that the building would have to be replaced.

For buildings that could be repaired, Muto and Krishnan looked at the components—drywall partitions, electrical and plumbing systems, sprinklers, and elevators, for example. Drawing from empirical data taken by other engineers on how these various parts hold up to stresses, they calculated IDR-dependent probabilities and costs for repair or replacement.

Muto emphasizes that this is a prototype study, based on a handful of specific buildings. But again, this kind of analysis will pave the way for more comprehensive studies, incorporating multiple earthquake scenarios and many different building types.

Which brings us back to the ShakeOut scenario. Krishnan and Muto applied their methods to estimate how many midsized, steel buildings would collapse under the 7.8-magnitude ShakeOut earthquake. They made a grid of 784 sites, each containing three buildings—the same pre- and post-1997 18-story office buildings from their earlier work, and a 19-story L-shaped structure designed according to 1997 building codes. The ShakeOut exercise also involved another team from UCLA that studied the response of reinforced-concrete buildings.

There are hundreds of buildings in the Los Angeles metro area more than 10 stories high, and by combining a census of these buildings with the simulation results, Muto and Krishnan recommended that the Shake-

Out drill should be conducted by assuming that eight tall buildings would collapse, 16 would be red-tagged—meaning that they're on the verge of collapsing and are unsafe to enter—24 buildings would be damaged enough to kill people, and 32 buildings would have visible damage resulting in injuries.

The ShakeOut event was designed to shake the public out of its complacency and remind everyone that the Big One is inevitable. If we do nothing to prepare ourselves, the consequences will be dire. But even researchers like Muto were surprised at how powerful the shaking was. And the results of their simulations were indeed serious. "The potential for catastrophe is pretty intimidating," Muto says.

DEAD TECHERS WALKING

On the Caltech campus, the drill was equally serious. When the clock struck 10 a.m. on that warm Thursday in November, the entire campus, along with millions of participants in eight counties—5.3 million people registered—ducked, covered, and held on. Throughout the day, the Institute practiced responding to various emergencies, such as power outages, fires, chemical spills, and casualties. Outside Beckman Auditorium and the Caltech Y, a few dozen people—mainly undergraduates—lay on the ground, groaning in pain. Many were covered in blood, courtesy of friends in Caltech's theater arts program. Each "victim" had specific injuries for emergency personnel to diagnose and treat. Some had minor cuts, some had bones sticking out of their flesh, and others were dying. Some were trapped under rubble—made from cardboard—and had to be pulled out.

The emergency responders were from the Caltech Health Advocate Program, which trains undergraduates in first aid, treating routine health problems, peer counseling, and how to respond to crises. Volunteers and current trainees took on the role of the injured. Overall, the exercise went well, says Marshall Grinstead, a junior, who suffered a minor scrape on his head as one of the "walking wounded." He didn't get one of the "cool injuries" that would have allowed him to ride the cart to the tennis courts by the gym, where the injured were treated. But, he adds, maybe that was better than playing dead. "People who were dead got really bored." Tired of lying there in the heat, some of them got up and walked around.

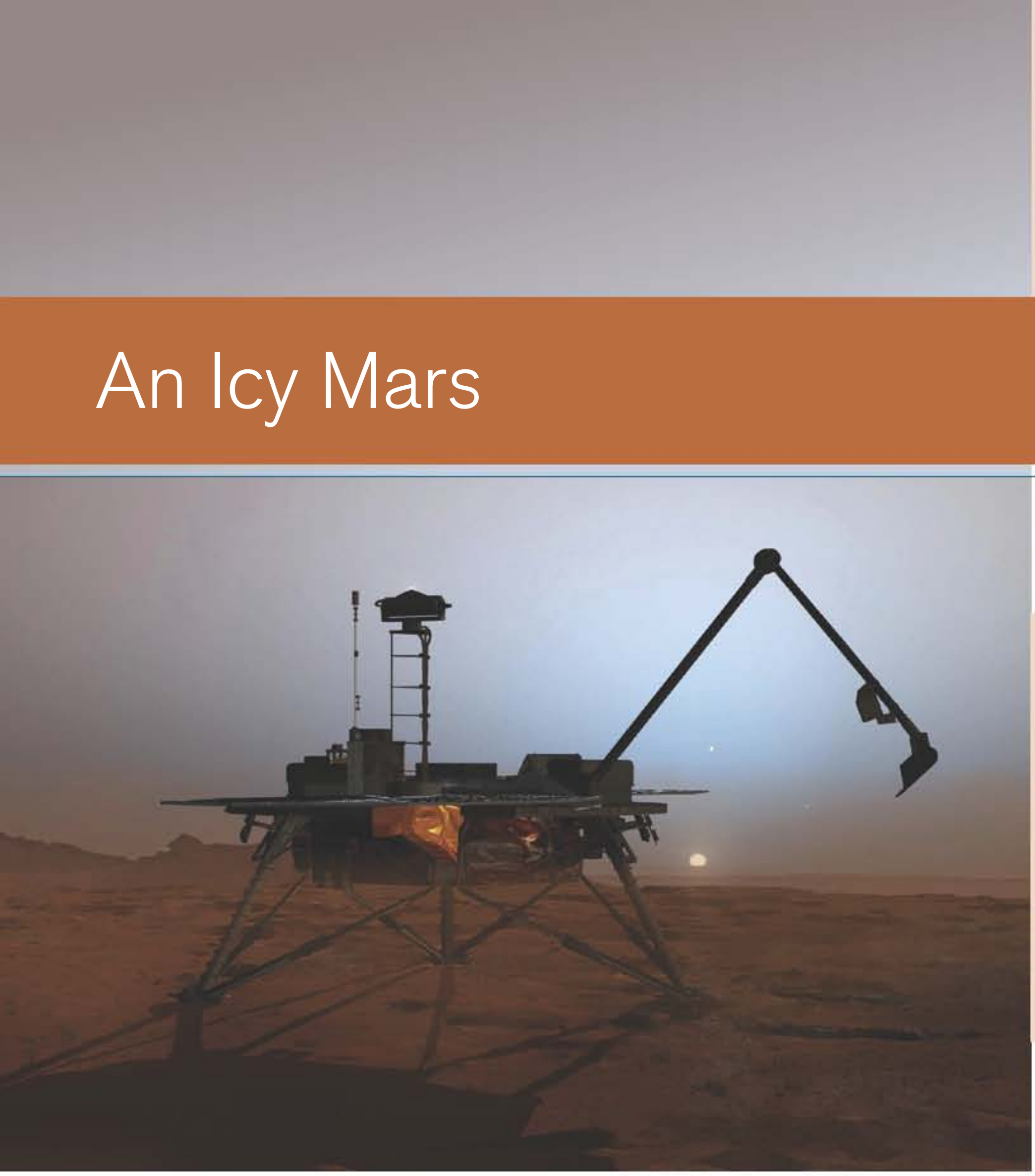
Individuals, local governments, schools, and businesses all participated in the ShakeOut, says the USGS's Ken Hudnut, a Caltech visiting associate in geophysics. In fact, there were more participants than the 5.3 million who registered, he says. "We clearly got a tremendous response from the public," he says. "It feels pretty good." Hudnut was involved in the entire effort, helping with the simulations and with the emergency response. "I've been doing earthquake research my whole career," he says, "and I feel like I haven't made as much of a societal impact until now."

As part of the drill, officials were able to test various emergency response systems, such as satellite phones. One of the biggest successes, according to Hudnut, was the interdisciplinary nature of the ShakeOut, which brought together sociologists, economists, seismologists, engineers, and even artists—the Art Center College of Design in Pasadena helped produce a video that depicted the catastrophic impacts of the ShakeOut.

"In the past, when we talk about the Big One on the San Andreas, we were not very specific," Hudnut says. An ambiguous danger doesn't always provoke the response a specific scenario would. But with the ShakeOut effort and studies like those of Krishnan's, the potential impacts have become clear and specific, and hopefully people have taken the message to heart. California governor Arnold Schwarzenegger, to his credit, was particularly interested in Krishnan and Muto's work, says Hudnut, who briefed the governor for the ShakeOut.

The next time we duck, cover, and hold on, it might not be a drill, and the collapsed buildings may be real. Seismologists say the stretch of the San Andreas south of Parkfield feels a big quake every 150 years or so. The Fort Tejon quake shook the northern segment in 1857. The southern part—where the ShakeOut rupture happened—last felt a quake more than 300 yearsr ago. For Southern California, the Big One's due.

As part of the ShakeOut drill at Caltech, student volunteers pretend to be injured while other volunteers tend to them in front of the Caltech Y.



An artist's rendition of the Phoenix lander shutting down operations as winter sets in.

An Icy Mars

With the Phoenix lander, scientists have visited a Martian polar region for the first time. Tasked with finding signs of water—and in particular, ice—and conditions suitable for life, Phoenix has returned a bounty of new knowledge.

Mars is not a hospitable place for humans. Farther away from the sun than Earth by more than 50 percent, its midsummer equatorial surface temperature barely reaches the freezing point of water. The Red Planet weighs one tenth as much as Earth and has an atmosphere that's one thousand times thinner. Yet, of all the planets in the solar system, Mars (along with Venus) is the most similar to our own. But it's Mars that has generated the most speculation about alien life—fictional and real, from television characters Marvin the Martian and Uncle Martin to what were thought to be microbes brought over on Martian meteorites—a discovery announced with great fanfare in 1996 on which the jury is still out. Mars's and Earth's axes have similar tilts, at 25.2 and 23.5 degrees, respectively, leading to comparable seasonal cycles. Both have had past changes in global climate, and both have polar ice caps.

Maybe the most exciting similarity is the presence of water, believed to be essential for life—at least, what we know of as life. Although abundant liquid water can't exist, since the thin atmosphere and frigid temperatures mean oceans, lakes, or rivers would either evaporate or freeze, Mars Global Surveyor, Odyssey, and the Exploration Rovers have sent back evidence showing that Mars has substantial water frozen at its poles. Plus, there may be conditions where tiny amounts of water are unfrozen—a few loose molecules might be able to wiggle around, creating an environment in which microbes may survive. Could the poles, then, be abodes for Martian life?

Enter NASA's Phoenix mission, led by the University of Arizona and JPL. With its successful landing in May on the arctic plain at latitude 68 degrees north—roughly equivalent to the Arctic Circle on Earth—Phoenix became the first probe to visit one of the Martian poles. Phoenix's goal was to look for

Right and center: Gullies in the walls of two meteor craters in Sirenum Terra's Newton Basin.
Far right: This approximate true-color rendering, taken by the Opportunity Rover, shows hematite pebbles—nicknamed "blueberries"—strewn across an area called Berry Bowl. Researchers say the blueberries probably formed when groundwater seeped through rock and reacted, depositing the hematite spheres.

By Marcus Y. Woo

signs of water: frozen and unfrozen, present and past. Scientists also wanted to search for places where life may exist, so-called habitability zones. In five months of digging and scraping, the craft returned a bounty of data, finding surprises in the soil, seeing wispy clouds and falling snow, and for the first time, touching cold, hard, Martian ice.

WATER, WATER EVERYWHERE?

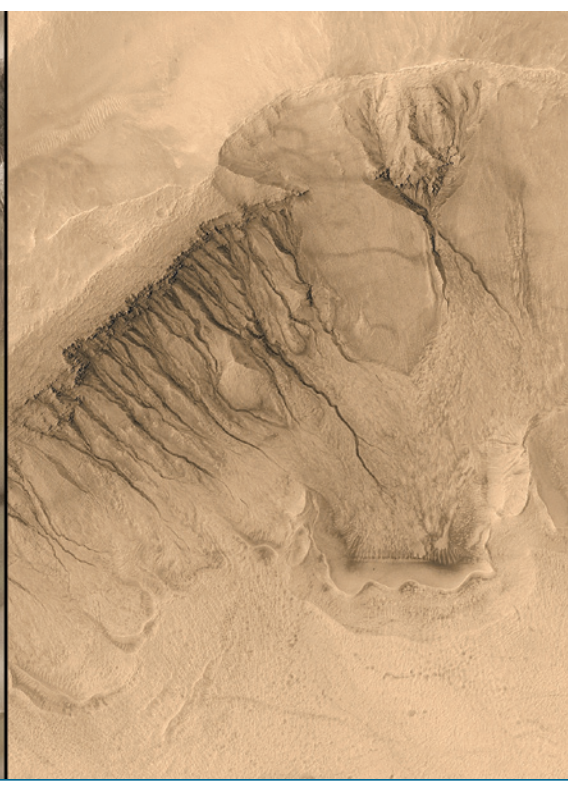
People have looked for water on Mars since at least the late 19th century, when Percival Lowell wrote about the canals he thought he saw crisscrossing the planet's surface. Since then, complex Martian waterways have been debunked, but the search for signs of water continues. In the 1970s, JPL's Viking orbiters photographed channels that appeared to have been carved by flowing water. Twenty years later, the Mars Global Surveyor found salt deposits at two craters called Terra Sirenum and Centauri Montes, suggesting they were sites where water once flowed. Over the last decade, a whole fleet of spacecraft has detected numerous signs of past—and perhaps present—liquid water, including gullies that had sprung into existence where no gullies had been before.

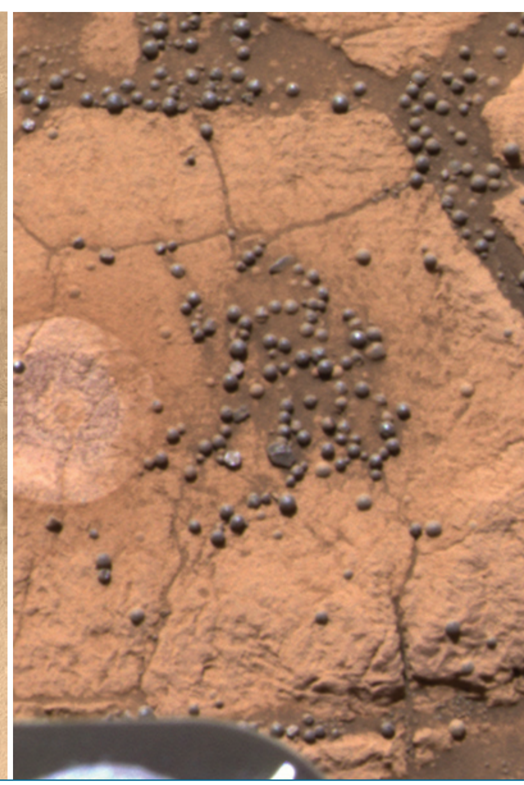
But the strongest evidence so far is in mineral deposits. The Mars Rover Opportunity found spherical pebbles of hematite, a type of iron oxide. Dubbed "blueberries" because of their size and shape, these objects may have cousins on Earth. Geologists from the University of Utah had analyzed similar hematite pebbles in southern Utah, and determined that they form when groundwater seeps through permeable rock and reacts, leaving behind minerals. After comparing the Utah pebbles to the Martian "blueberries," the researchers concluded both were formed in the same way.

But if Mars was once awash in liquid water, where did it all go? Though scientists are still unsure, one leading theory points to the once-molten nickel-iron core as the culprit. A molten core, like Earth's, is a churning furnace—a dynamo that generates an electric current. The current creates a magnetic field, a bubble that protects the planet's atmosphere from the solar wind.

Mars's core became inert roughly four billion years ago, allowing particles from the solar wind to strip away its atmosphere. As a result, any surface water evaporated and much of the water vapor was lost into space. The atmosphere also trapped heat, so that, as the air thinned out, Mars cooled dramatically.

With any liquid water that may have existed now gone, opportunities to surf on Mars may be slim. But sports enthusiasts need not despair—in 2002, the Mars Odyssey orbiter detected the signature of hydrogen,





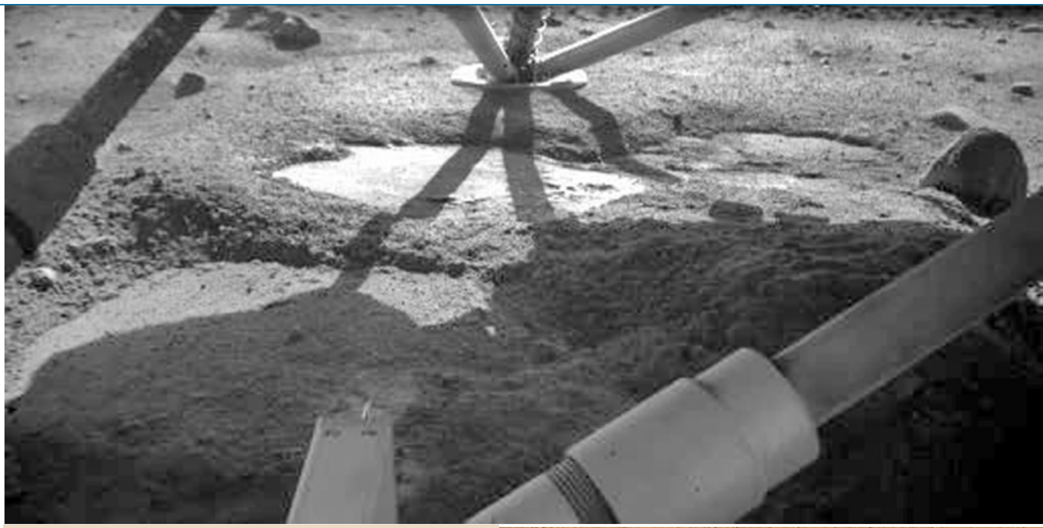
Given that more than half of all previous attempts to land on Mars had failed, the mission was anything but a slam dunk. The landing was "eight minutes of terror."

a proxy for water, in the top meter or so of soil near the south pole. Mars may abound in frozen water—ice skating, anyone?

Scientists also want to study the poles because of what they reveal about Mars's climate history. The tilt in Mars's axis has shifted over the eons, meaning that in the past the northern hemisphere pointed more directly toward the sun, resulting in warmer summers.

NASA had already sent the Mars Polar Lander to the southern polar region in 1998, but it crashed upon arrival. Over the past decade, NASA's slogan for exploring Mars has been to "follow the water," making the search for evidence of that life-affirming molecule central to each mission. Now that it appeared water ice might be sitting tantalizingly below the surface, NASA sought redemption in another polar lander. This time, however, the plan was to visit the north pole. In 2007, when Phoenix was to be launched, the north pole was the easiest to get to. The north pole also has water ice, which is exposed during the summer, unlike in the south. In fact, the north polar ice cap is Mars's primary source of water.

Named after the mythical bird that rose from its own ashes, Phoenix was a spacecraft reborn. Researchers built the probe by combining three instruments from the first Polar Lander (two landers had been built) and the body and two instruments from the Mars Surveyor 2001 Lander, a follow-on craft that had been built by Lockheed Martin Space Systems in 2000 but then shelved after the loss of the first lander. On



Above: This picture taken of the area below the lander shows a smooth, flat patch that looks like ice, prompting the scientists to exclaim, "Holy cow!"

Right: Called Dodo-Goldilocks, this trench revealed white stuff that has been confirmed to be water ice.

August 4, 2007, a Delta II rocket launched Phoenix on its 10-month journey to the Red Planet.

Given that more than half of all previous attempts to land on Mars had failed, the mission was anything but a slam dunk. The landing was "eight minutes of terror," says Leslie Tamppari of JPL, the mission's project scientist and a Phoenix coinvestigator. (Peter Smith, of the Lunar and Planetary Laboratory at the University of Arizona is the principal investigator.) Because of its bigger payload, Phoenix couldn't use airbags to cushion its fall like the highly successful Mars rovers had. It had to use thrusters to slow its descent—as the first Mars Polar Lander had—adding another element of uncertainty. After all, the Polar Lander is believed to have been lost when its thrusters cut off too soon. It took dozens of people working full time for four years to plan the landing, according to Tamppari. When the craft touched down safely on May 25, 2008, "there was a huge eruption of celebration," Tamppari recalls. "It was a fabulous day."

HOLY COW!

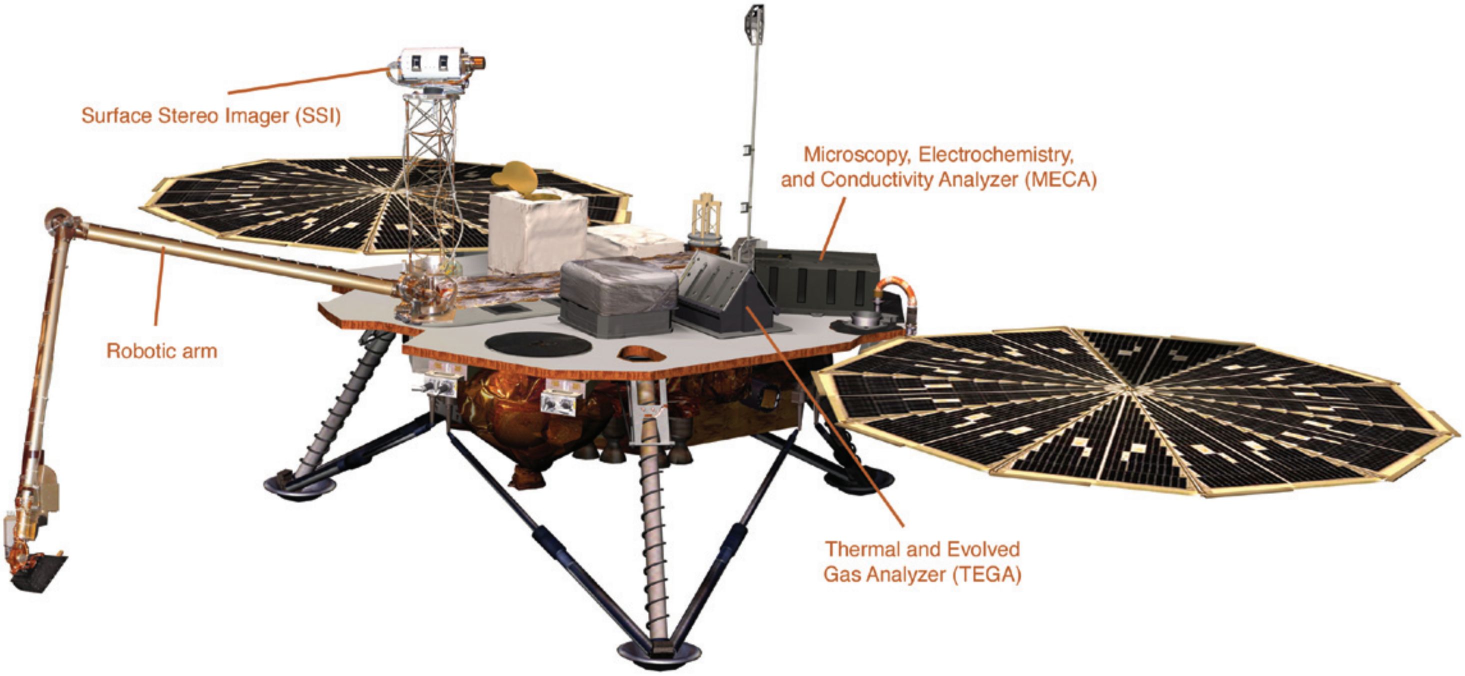
Within a few hours, Phoenix had sent back its first photos. The terrain was covered with polygon-shaped features indicative of subsurface ice. The shapes are formed when ice temperatures change, cracking the surface. Dirt falls into these cracks and keeps them open. "It was really an incredible moment to be one of the first people on Earth to view these pictures of Mars," Tamppari says about the flat Martian surface dotted with rocks. "From a geologist's perspective, this is beautiful terrain."

Scientists converged on mission headquarters in Tucson, Arizona—even though Phoenix, some 185 kilometers up Interstate 10, might've been more appropriate, Tamppari points out. More than 80 scientists, engineers, and students would spend the next three months in Tucson living and working on Mars time. The Martian day, called a sol, is about 40 minutes longer than an Earth day, meaning that the team's day-night cycle slowly diverged from that of the world around them. After about five weeks, they were a day out of synch.

On just the sixth sol, Phoenix took what Tamppari calls the mission's "holy-cow image"—a picture of the area just below the lander, where the thrusters had blown away the top layer of soil, exposing a smooth, white surface. It appeared as if Phoenix had already found the top item on its list, ice. But scientists couldn't confirm this discovery until they got a closer look.

Phoenix's 2.35-meter robot arm dug several shallow trenches around the site, each only a few centimeters deep. The first trench, called Dodo-Goldilocks (the team named all the sites after fairy tales), revealed white patches, bright against the dark red of the Martian soil. Still, scientists couldn't be sure, because the white stuff could also be salt deposits, another item that Phoenix hoped to find. But when some of the white patches shrank over the next few days, scientists became convinced that they had found ice. In the thin, Martian atmosphere, ice sublimates—it goes from solid to gas, skipping the liquid stage. Salt doesn't do that. It stays put. For the first time, Martian ice was within a robotic arm's reach.

Over the next few weeks, Phoenix would scoop up some of the suspected ice and deposit it in one of its instruments, the Thermal and Evolved Gas Analyzer (TEGA). TEGA is a set of eight identical ovens, each about the size of a ball-point pen's ink cartridge, that can slowly heat a sample to



temperatures up to 1,000 degrees Celsius. Each oven can only be used once. Heating a sample releases any volatile material, and a built-in mass spectrometer identifies atoms, molecules, or molecular fragments. Tamppari and principal investigator Peter Smith compare it to baking cookies at home. By smelling the scents wafting through the house, hungry guests can tell the difference between chocolate-chip and oatmeal-raisin. After baking the samples, TEGA confirmed that the white stuff was indeed water ice. This procedure proved tougher than anticipated, since the clumpy soil kept getting caught on the screen covering the ovens that was supposed to keep large particles from clogging the tiny chambers.

Snow White, another trench dug two meters away, also uncovered ice. But this ice wasn't bright and white—it was dirty. Scientists had assumed that most of the ice on Mars formed when water vapor seeped into the soil and froze, creating a thin, uniform ice layer everywhere. The fact that pristine and dirty ice were found right next to each other shows a variability that Tamppari says surprised the scientists.

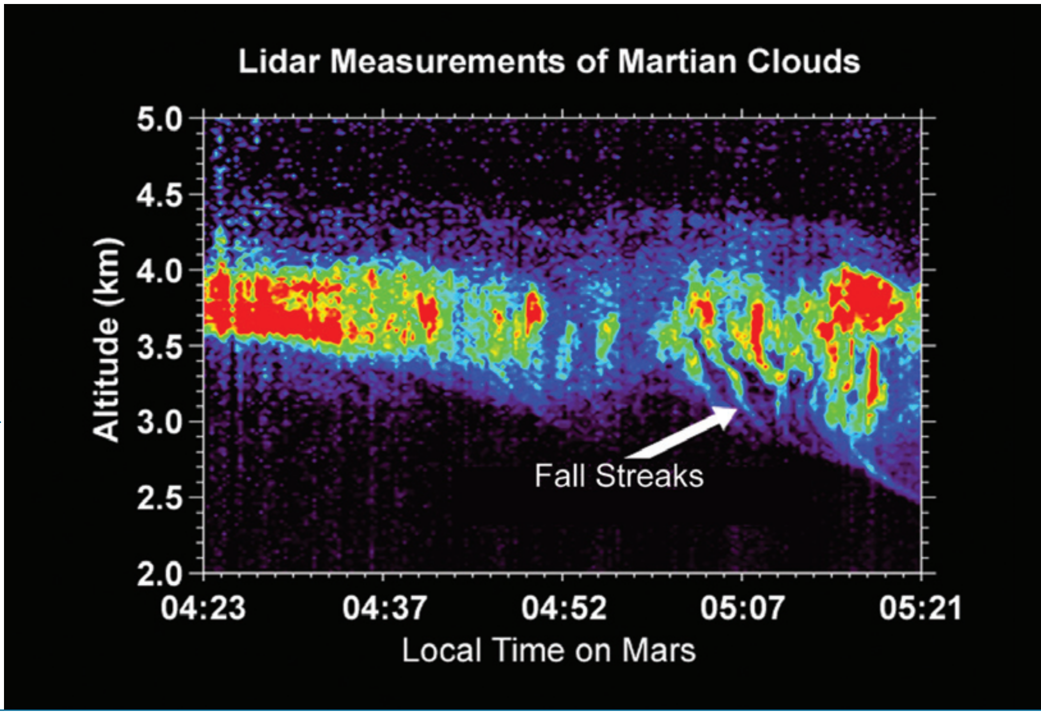
In addition to ice, TEGA found carbonates, a class of minerals formed when water, carbon dioxide, and other minerals react. Given all the carbon dioxide in Mars's atmosphere, any past water would have left the soil with abundant amounts of carbonates. Most of the carbonates proved to be calcium carbonate, with possibly other kinds as well.

The lander was also equipped with an instrument called the Microscopy, Electrochemistry, and Conductivity Analyzer (MECA), part of which is a wet chemistry lab that dissolves bits of soil for analysis, helping to determine whether the site is suitable for life. Scientists found the soil to be slightly alkaline, with a pH just above 8—comparable to tap water, and friendly for life.

Curiously, this measurement differed from what the rovers found in the equatorial region, Tamppari says. There, the soil was slightly acidic—a pH just below 7. "Something different has happened," she says. "These two areas were not created equally." The polar regions also differed in that Phoenix has so far not found any sulfates, which were present along the equator. Further analysis may still reveal sulfates, however.

In another surprise, MECA found a molecule called perchlorate in the soil. Perchlorate is often found in rocket fuel—although not Phoenix's, whose descent engine used pure hydrazine. Perchlorate is an oxidant that can break down organic molecules and is toxic to humans. But it also occurs on Earth naturally—in particular, in Chile's Atacama Desert, where some microbes use it as a source of energy, Tamppari says. So scientists still don't know whether it's good or bad for life.

Phoenix also has a lidar, analogous to a radar device that uses light instead of radio waves, that has gathered the most detailed data ever taken on the lowest five to eight kilometers of the atmosphere. Called the Martian boundary layer, this region is where surface and atmospheric temperature changes cause the air to mix. The instrument fires a laser into the sky, and the light bounces off particles of dust or ice. The time it takes for the laser to bounce back tells how high the particles are, and the amount of light reflected back tells how many particles there are. Using the lidar and Phoenix's cameras, scientists tracked the formation of clouds at night and, for the first time, saw falling snow, which sublimated before hitting



A thin layer of water frost forms on the ground around the Phoenix lander at 6 a.m. on August 14, 2008.

the ground.

Tamppari had previously studied water vapor in the Martian atmosphere, using infrared instruments aboard Mars orbiters to analyze clouds. The smallest areas the orbiter could resolve were 60 to 100 kilometers wide. As a result, she was surprised when Phoenix snapped pictures of wispy clouds drifting across the sky. "I thought the clouds would be more of a uniform haze," she says. Instead, they spanned a wide range of densities.

CONSUMED BY ICE

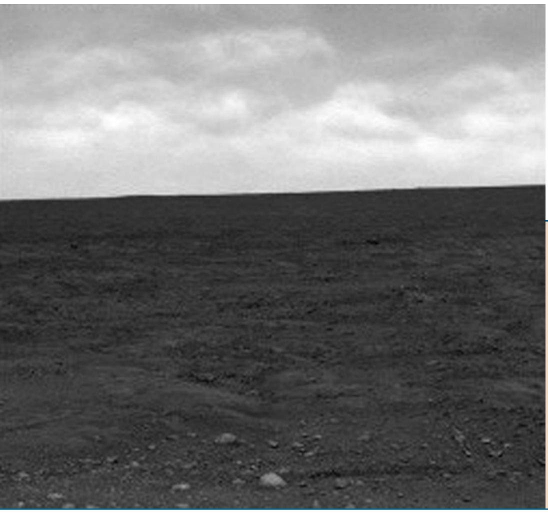
Phoenix landed during the northern hemisphere's summer, when the daytime temperature was around a balmy zero degrees Celsius. As the weeks passed, temperatures dwindled and the air pressure dropped. Water frost started to form on the ground. Winter would bring increasing hours of darkness, and without the sun to feed its solar panels, Phoenix would slowly die. In late October, the lander was running on its last gasps of power, struggling to recharge itself. Communication with the craft became intermittent. By the beginning of November, Phoenix went silent for good.

Originally slated to last three months, Phoenix had managed to go for five. This may seem like a short lifetime, especially after we've been spoiled by the rovers that have turned a 90-day mission into an ongoing five-year sojourn. These rovers, however, are in the equatorial region, where sunlight will always supply power. The poles are a far harsher place, and Phoenix sits frozen, powerless, and alone in the dark. The spacecraft will be encased in a thick layer of dry ice, and the lander's electronics are unlikely to survive such bitter cold.

When summer returns in a few months, scientists will try to nudge Phoenix awake. The lander can switch into a mode called Lazarus that allows it to recharge itself and return to life. But any number of things could happen in the meantime, Tamppari says. Accumulating snow and ice could crush the craft and break its solar panels. "Nevertheless, we'll plan to listen for the spacecraft—just in case."

So far, there's no plan to revisit the poles. The next mission to Mars will be the Mars Science Laboratory, a Mini Cooper–sized rover destined for more temperate climates, whose 2009 launch date has just been postponed for two years.

The phoenix, a symbol of immortality, renews itself in fire. From its own ashes, the bird rises to live again. Consumed not by fire, but by ice, the Phoenix lander, though, has probably taken its last picture and sent its last byte of data. The most groundbreaking results—the discovery of ice, carbonates, and perchlorate; the measurements of Mars's alkaline soil; and the accumulated weather reports—will soon be published in a series of four papers in the journal *Science*. Indeed, the spacecraft has provided enough data to keep scientists busy for years, conferring on this phoenix its own kind of immortality. E&S



Far left: The lidar provides a cross section through the clouds passing overhead. Falling snow can be seen as vertical streaks at the base of the cloud beginning at about 5 a.m., Mars time. At altitudes of around three kilometers, fast winds curve the streaks.

Left: During the early afternoon hours of September 18, 2008, the Surface Stereo Imager captured this image of clouds moving eastward across the Martian horizon.

OBITUARIES

GEORGE W. HOUSNER

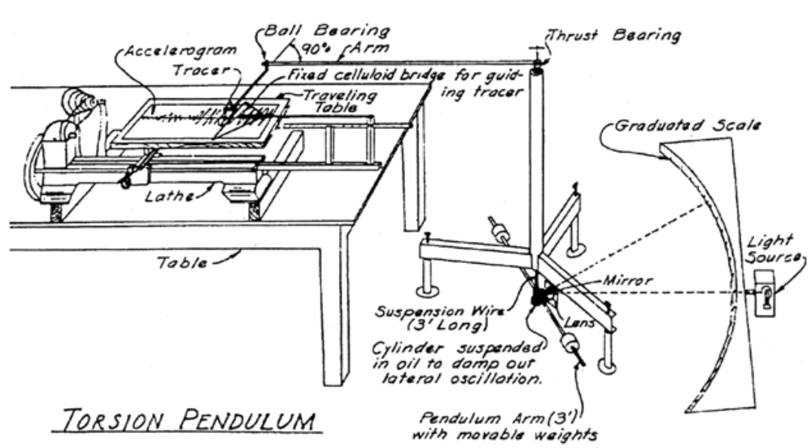
1910-2008

George W. Housner, the Braun Professor of Engineering, Emeritus, often considered the father of earthquake engineering, died on November 10 of natural causes. He was 97.

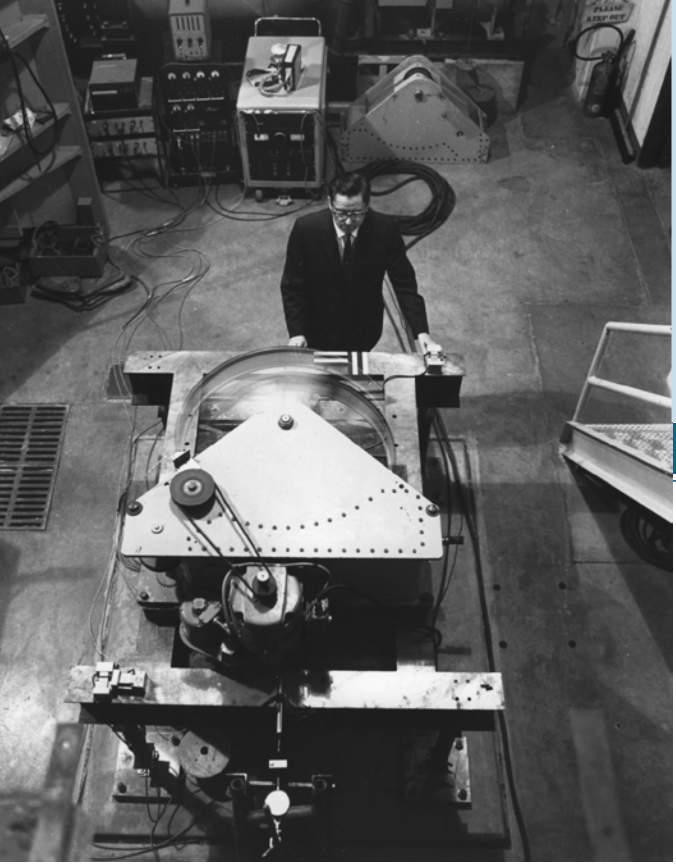
Born in Saginaw, Michigan, in 1910, Housner received his bachelor's degree in civil engineering from the University of Michigan–Ann Arbor in 1933. He earned his MS at Caltech in 1934, and then took five years off to work as an engineer, designing bridges, schools, and dams. His interest in making buildings earthquake-resistant began during this stint in the workaday world—the magnitude-6.4 Long Beach quake had rocked the Southland just months before his arrival, killing 115 people and causing some $40 million in damage.

Housner returned to campus in 1939, earning his PhD in 1941 under Romeo Martel, who became interested in the earthquake-resistant design of buildings after the magnitude-8+ Great Kanto Quake and firestorm leveled Tokyo in 1923. Housner's thesis, *An Investigation of the Effects of Earthquakes on Buildings*, "is so fundamental that nobody ever cites it explicitly any more," says John Hall, professor of civil engineering. It was indeed the seed of a new field. In his oral history, Housner recalls the task of trying to convert an earthquake accelerogram—a paper record of the ground motion at a specific site—into a "response spectrum," which predicts how a building of a given height at that location would behave upon experiencing that shaking. "I first did that for my thesis. And the very first time we calculated it—we did it by pencil and paper, which involved drawing the accelerogram and multiplying and integrating—it took about a day for one point on the spectrum . . . . [The torsion pendulum] speeded it up from one day to about 15 minutes. Well, that was a big advance, about 30 times. But then later we developed an electrical way of doing it and we'd get a point in maybe 15 seconds. Now [in 1984], 15 seconds on the digital computer, and we get 500 points."

Housner put aside his calculations to advise the Army Air Forces during World War II. As a civilian member of the National Research Council, he was in North Africa and Italy from 1943 to 1945. His first act upon arrival was to help retrain the bomber crews' machine gunners, who were being taught to "lead" enemy fighters as if shooting at a formation of Canada geese from a blind. But from a speeding aircraft, says Hall, "you usually have to aim behind the target, which is not intuitive. You can increase the hit rate by an order of magnitude." The booklet Housner's group prepared, entitled *Get That Fighter*, became standard issue. "They even had charts posted on the walls of the planes," says Hall. Soon after, Housner got involved in planning the bombing raid on Ploiesti, Romania—Nazi Germany's only oil field, and the most heavily defended target in the Reich. The defenses included barrage balloons, tethered by steel cables at an altitude of about 2,000 feet. The idea was that low-flying bombers would hit the cables and spin out of control, but Housner's analysis of the stress waves that would run up and down the cable when a wing hit it proved that the cable would snap instantly above a certain impact velocity. Reassured, the pilots flew—and inspections of the returning planes showed grooves gouged into the wings where cables had been hit without the pilots knowing it. Later, in Italy, Housner read an intelligence report on a list of standard equipment available to the German engineers in charge of rebuilding bombed-out bridges, and he noticed that the longest available I-beam was 15 meters. He persuaded



Housner built this device for his PhD work. The torsion pendulum, standing in for a building, is set in motion by manually tracing an earthquake accelerogram placed on a table moved at constant speed by a lathe motor.



Housner with a rooftop-shaking machine in a 1966 photo. Dino Morelli's design consisted of two off-center baskets that counterrotated on a common vertical axis at a speed precisely set by Tom Caughey's controllers. With the baskets loaded with several hundred pounds of lead weights, and the machine set to match Millikan Library's .85-second resonance period, it moved the building back and forth a quarter of an inch.

the operations planners to target bridges whose spans between piers were longer than 15 meters, as they would be impossible to repair without building a new pier in the middle of the bombed-out span to support the I-beams. This, in turn, would keep the bridges out of service for a much longer time. For this and many other contributions, he was given the Distinguished Civilian Service Award by the War Department.

Returning to Caltech as an assistant professor of applied mechanics in 1945, Housner coauthored two textbooks on mechanics with professor Donald Hudson (BS '38, MS '39, PhD '42) and a book on stresses and strains with professor Thad Vreeland (BS '49, MS '50, PhD '52). Though now out of print, they live on. "They were some of the best-written texts ever," says Hall, with "clear and concise explanations that dealt with complex issues. A lot of the modern texts borrow his ideas, and even his problems."

During those early postwar years, Housner established his reputation as an intellectual leader in applied-mechanics research. He tackled such problems as flow-induced vibrations in pipelines, the sloshing of fluids in large storage tanks, and hydrodynamic pressure on dams during earthquakes.

"He was a fundamental, independent, and creative thinker, with great intuition and practicality," Hall said. "Solving problems was what he was designed to do. He'd look at a problem, quantify it in some way, and come up with a solution."

This attribute would come into full flower in the 1950s, when he and mechanical engineer Hudson started developing instruments to measure how buildings responded to being shaken—work funded, oddly enough, by the Office of Naval Research. These strong-motion accelerographs, when installed on several floors of a tall building, allowed the engineers to determine the building's natural vibrational modes and how those modes damped themselves out. Some of this information could be gleaned from the small jitters of a building at rest, but to really put a building through its paces, it needed to be moved on command. To this end, Housner, Hudson, and professors Tom Caughey (PhD '54) and Dino Morelli (MS '45, PhD '46) built a rooftop-mounted shaking machine. Modern versions of these machines—one of which sits atop Caltech's nine-story Millikan Library—are now in use all over the world.

These studies first saw practical application in early 1960s, with the design of the 40-story Union Bank building in downtown Los Angeles. The Connecticut General Life Insurance Company, which built the building, instructed the architect to go to Caltech for advice on earthquake-resistant design. Housner and Paul Jennings (MS '60, PhD '63, now professor of civil engineering and applied mechanics, emeritus) took inventory of the known faults in the vicinity, and estimated the ground shaking at the building site that would result from a plausible earthquake on each fault. As Housner remarked in his oral history for the Caltech Archives, "We then showed them how to calculate how the building would respond [to that shaking]. And we helped them make the design. After that, all the high-rise buildings in Los Angeles were done in the same way."

"Working with George on this important, practical project was a great learning experience for a young professor," Jennings recalls. Housner and Jennings later went on to consult on the design of the twin 52-story ARCO towers, the 55-story Security Pacific Bank building, and many other structures. "In a sense," said Housner, "those buildings had experienced some four or five [strong] earthquakes before they were built."

Even before construction on the Union Bank tower began in 1965, the wisdom of this approach became self-evident. On March 27, 1964, a magnitude-9.2 temblor made the high-rises in Anchorage, Alaska—all four of them; two of 14 stories, and one each of 8 and 10 floors—uninhabitable, along with innumerable lesser structures. Housner was appointed chair of a National Academy of Sciences engineering committee to evaluate the damage. The entire NAS report—the first such comprehensive scientific study of a natural disaster—filled nine volumes, with the engineering book running 1,190 pages.

The nation's attention was now focused on earthquakes, and the head of the Building and Safety Department for the city of Los Angeles, John Monning (BS '33), seized the op-

Housner received the National Medal of Science from President Ronald Reagan in a White House ceremony in 1988 for his "profound and decisive influence on the development of earthquake engineering worldwide."

portunity to persuade the city council to require that all new buildings of 10 stories or higher be equipped, at the owner's expense, with three strong-motion accelerographs at basement, roof, and mid height. (Housner and Hudson had drawn up specs for a design that could be built cheaply, and had persuaded Teledyne, a local geophysical instrument maker, to manufacture it—more than 10,000 of its successors have now been sold worldwide.)

Thus, when the magnitude-6.6 San Fernando quake struck on February 9, 1971, Housner recalled, "we were able to get all sorts of records. We got more records on that earthquake than out of all the earthquakes in the world before that." And with mainframe computers having become capable of some serious number crunching, they were able to validate his and Jennings' high-rise design methods against the accelerograms obtained in the earthquake. "The Building Department in L.A. said, 'Well, that's good enough for us. We can now force through the requirement that all buildings over 16 stories be designed on a dynamic basis'"—that is, to resist the dynamic lateral forces of an earthquake rather than a static "equivalent" lateral load (a very strong wind, essentially, which was the best proxy previously available), as previous versions of the code had specified. Where Los Angeles leads, others follow, and this is now standard practice for the codes governing the design of tall buildings in seismic areas everywhere.

Housner was keenly interested in other types of structures as well, consulting over the years on San Francisco's Bay Area Rapid Transit system, the Trans-Arabian Pipeline, nuclear facilities, ports, and offshore oil platforms. In the 1950s, the California State Water Project—a sprawling undertaking that brings water from the rivers of Northern California and the high Sierra to the thirsty cities and farms of the rest of the state—was being launched. The project includes some 20 big dams, a dozen or so large pumping stations—several of them near the San Andreas fault—to hoist the water over the mountains, and the California Aqueduct itself, which crosses the fault three times. Lobbying by Housner and others led to the creation of a seismic safety advisory board, chaired by Housner, in 1962. "We prepared a recommendation based on my research and told them what the strong shaking would likely be and what they should do. And they adopted the procedure. That was the first time such modern procedures had been used on dams and pumping plants. So we set a precedent; now all over the world they do that the way we recommended it."

Housner also spent a lot of time abroad, and in correspondence with foreign colleagues. "I don't think it's fully appreciated how much he worked for international cooperation," says Hall. "I came on him in the copier room once, wrapping up this parcel of books from his own collection to send to this guy he'd been writing to at the University of Bohol, in the Philippines. And I thought to myself, there he is, sowing another seed in the world. Encouraging somebody. Most of us would be too busy to bother."

Housner began a very active retirement in 1981, coming out of it to chair yet another disaster inquiry, this one of the magnitude-6.9 Loma Prieta quake of 1989 that caused the collapse of the San Francisco–Oakland Bay Bridge and several segments of the Nimitz Freeway (I-880) in Oakland. "The resulting report, *Competing Against Time*, was very effective, and serves as a model for such post-earthquake inquiries," says Jennings.

A lifelong bachelor who had always enjoyed teaching, Housner began to disburse his estate to the Institute after retirement. He established an endowment for grad students and postdocs in earthquake engineering, followed by the Housner Student Discovery Fund to support undergrads in essentially any scholarly endeavor. Next came an unrestricted endowment to the Caltech Y. His will contains a bequest to endow a chair in any field, and his collection of some 200 rare books, amassed on his world travels and mostly engineering- or science-related, is now in the Caltech Archives. He also supported local musical and artistic organizations, particularly the Coleman Chamber Concert Series.

Housner was a member of the National Academy of Engineering, the National Academy of Sciences, and the American Academy of Arts and Sciences. He was a founding member of the Earthquake Engineering Research Institute, which annually awards a medal in his name, and was instrumental in the formation of the International Association for Earthquake Engineering and Caltech's Earthquake Research Affiliates. In 1981, he was given the Harry Fielding Reid Medal from the Seismological Society of America, and in 1988, the National Medal of Science. He was named a Caltech Distinguished Alumnus in 2006. —*DS* e&s

JACQUELYN DOE BONNER

1917-2008

Jackie Bonner, former editor of *Engineering & Science*, died in Pasadena on November 21 at the age of 91. A longtime member of the Caltech community, Jackie was born in Clifton, Arizona, and grew up in Arizona, Idaho, and California. She attended Idaho State University, and later was a student at UC Berkeley.

In 1939 Jackie married Wesley Hershey, and the couple moved to Pasadena in 1946, when he was hired to serve as executive secretary of the Caltech Y. As Mrs. Hershey, she hosted hundreds of Caltech Y events and social gatherings.

Jackie began paid employment at Caltech in 1962 as an editorial assistant in the Industrial Relations Center and joined the Publications staff in 1965. She became associate editor of *E&S* in 1968 and managing editor three years later. When legendary *E&S* editor Ed Hutchings retired in 1979 (he had been hired as the magazine's first professional editor in 1948), Jackie was the natural successor, and for the next five years produced a publication that continued Ed's style of clear, straightforward writing, careful editing, and tenacity in nagging faculty to explain their work in simple English—a legacy that she, in turn, bequeathed to those who succeeded her. Her close attention to editing, in particular, influenced many of her colleagues. She left her own creative mark in the section of *E&S* called Random Walk—her title—which she started in 1981, and which, though it has migrated from the back to the front of the magazine, still exists.

In 1973 Jackie had married her second husband, Lyman Bonner (PhD '35), a rocket propellant expert and Caltech administrator, and in 1984 she and Lyman decided to take less demanding, half-time positions at the Institute. She continued working as a senior editor on the Publications staff until she retired in 1988.

Jackie was an avid reader throughout her life and a long-standing member of the Neighborhood Church and the League of Women Voters. She was predeceased by both of her husbands and is survived by her daughters, Kay Hershey Loughman, Margaret Hershey Lester, and Susan Hershey; stepchildren Allen and Philip Bonner and Lynn Bonner Bernstein; and eight grandchildren and stepgrandchildren. e&s

KITAEV WINS "GENIUS" AWARD

Alexei Kitaev, professor of theoretical physics and computer science, has been named a MacArthur Fellow. Often referred to as the "genius" awards, the five-year, $500,000 grants are awarded annually to 25 creative, original individuals.

Kitaev has made important theoretical contributions to a wide array of topics within condensed-matter physics, including quasicrystals and quantum chaos. More recently, he has devoted considerable attention to the uses of quantum physics in computation. Though his work focuses mainly on the conceptual level, he also participates in "hands-on" efforts to develop working quantum computers.

Kitaev says he was "very surprised" when he learned of the honor. "I didn't know what the award was at first," admits Kitaev, who was born and educated in Russia. "But then I looked up the names of people who have previously received a MacArthur award, and saw that they are very good scientists. I am excited and honored to be in the same group with them."

"We are thrilled that Alexei has received this well-deserved honor," says Andrew Lange, the Goldberger Professor of Physics and chair of the Division of Physics, Mathematics and Astronomy. "He is a stunningly original thinker who has made profound theoretical contributions to both quantum computing and condensed-matter physics." —*LO* e&s

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