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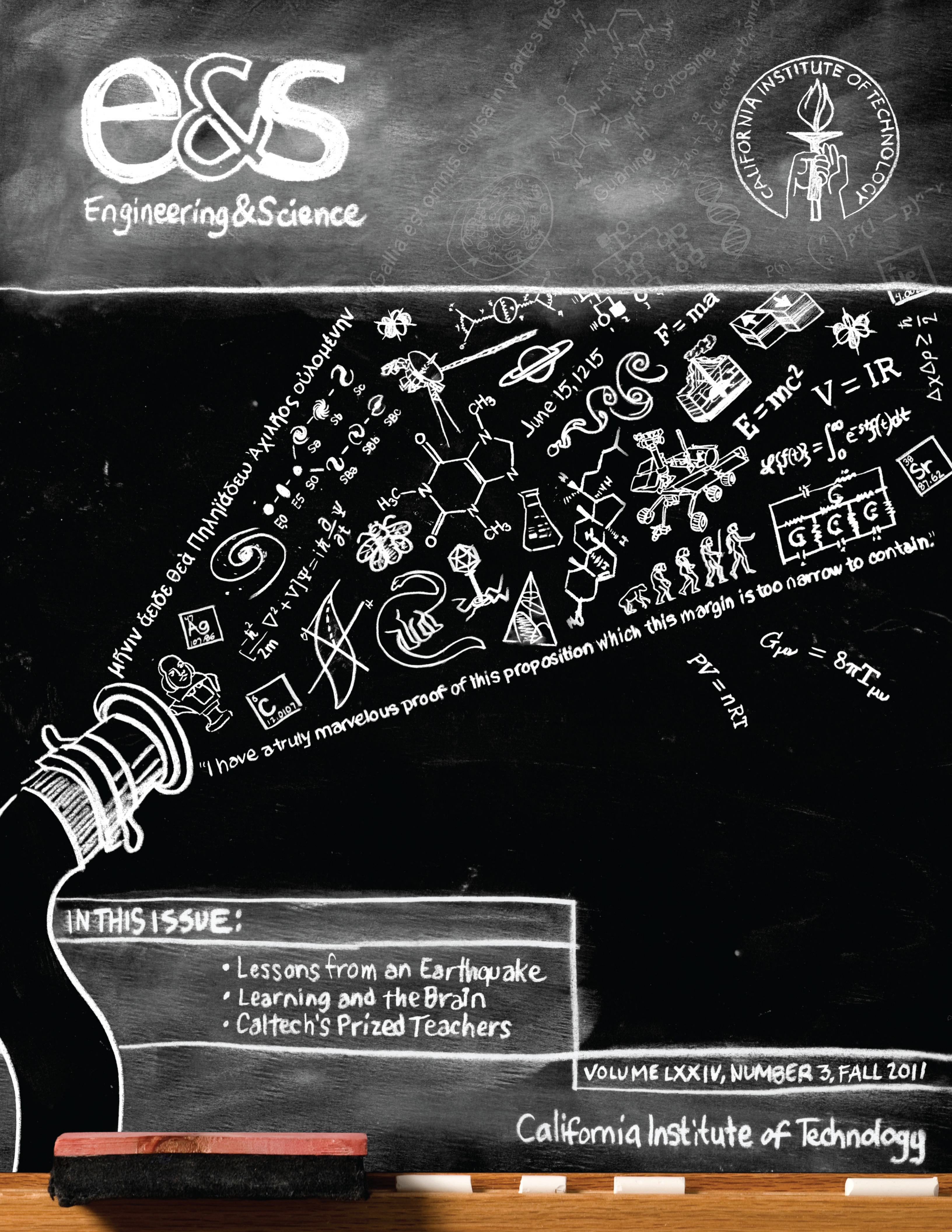
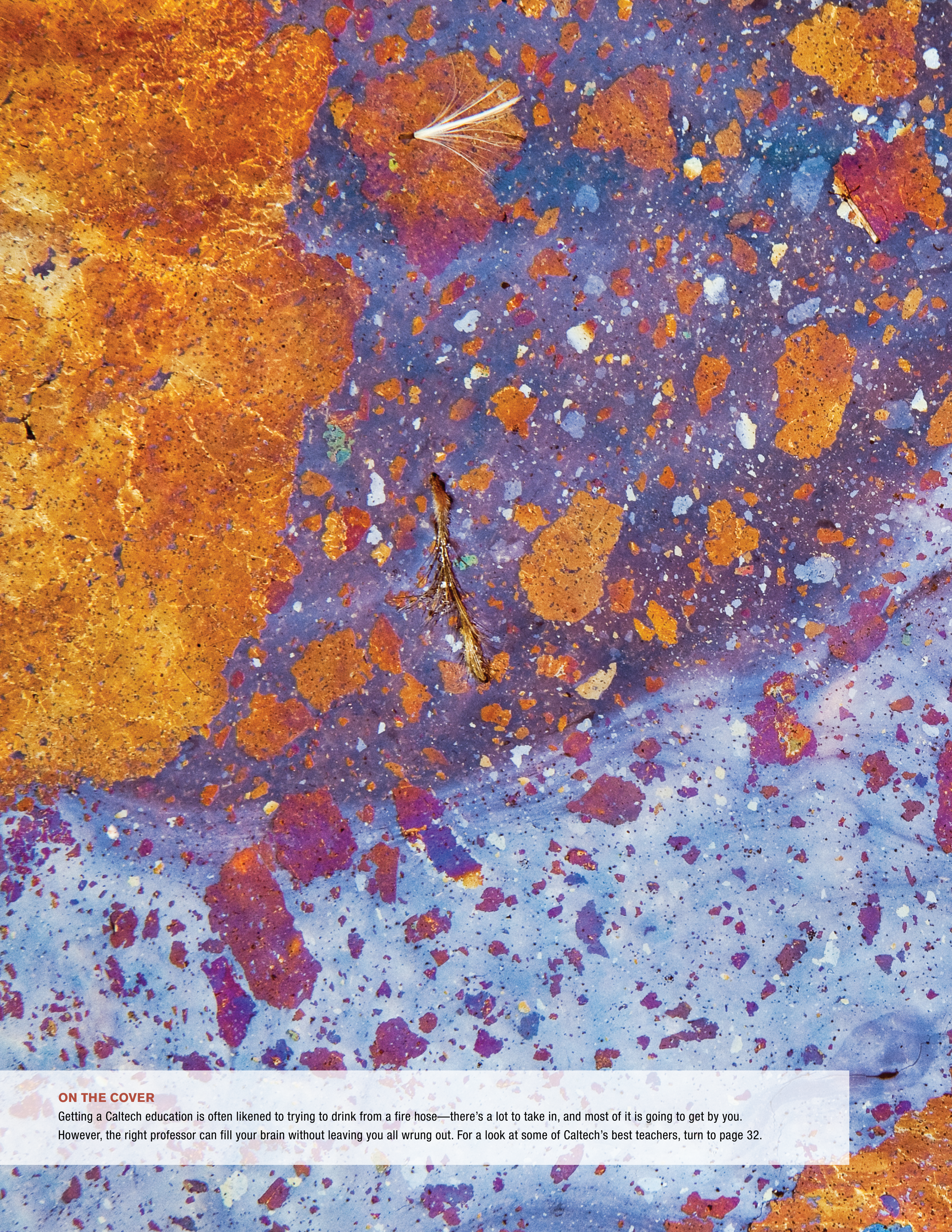


IN THIS ISSUE:

- Lessons from an Earthquake
- Learning and the Brain
- Caltech's Prized Teachers

VOLUME LXXIV, NUMBER 3, FALL 2011

California Institute of Technology



ON THE COVER

Getting a Caltech education is often likened to trying to drink from a fire hose—there's a lot to take in, and most of it is going to get by you. However, the right professor can fill your brain without leaving you all wrung out. For a look at some of Caltech's best teachers, turn to page 32.

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WHAT AM I LOOKING AT?

A thin layer of oily molecules from decaying leaves lend an iridescent sheen to a puddle. Scientists are trained to see what lies beneath; artists look for what lies beyond. Some people do both. Photo by grad student Floris van Breugel, who also won first prize for another photo, *Fluorescent Treasures*, in Caltech's third annual Art of Science competition last June.

DEAR ALUMNI AND FRIENDS OF CALTECH,

This issue of *E&S*, coming just as Caltech's students are returning—or arriving for the very first time—is about education in its many forms. The spotlight is on the day-to-day activity of learning, a process that occurs in Caltech's classrooms, in our laboratories and observatories, in our halls and Houses, outside the Red Door and inside the Athenaeum.

What makes Caltech unique is our focus—on education, on science and engineering, but most of all, on giving everyone at the Institute the means and flexibility to pursue his or her best ideas. We accept the best students, hire the best people and, once they are here, we give them the support and freedom to follow their curiosity.

That said, nothing in here is unusual for Caltech.

It is not unusual to find our researchers looking at the minutest details of learning, from the molecular level up. (See page 14.) It is not unusual—though it may be somewhat surprising—to learn that our scientists are examining not only learning's mechanisms, but what those systems mean in terms of decision making and human behavior.

It is not unusual for an undergraduate like Grayson Chadwick to sit down with a great scientist and mentor such as Dr. Alice Huang (see page 22) and talk about science and the future (though it isn't usually done in front of a photographer).

It is not unusual for scientists with different perspectives to pool their insights, as in the analysis of last March's 9.0 Tohoku-Oki earthquake in Japan. (See page 26.)

And it is not unusual for high-level scientists to be named among the Institute's finest teachers. (See page 32.) The Feynman Prize winners exemplify how learning can be made exhilarating, and how the process of teaching changes with each individual who undertakes the challenge.

Caltech is a place that is structured for learning; it is a place where we teach our students—and one another—how to learn. And in this and every issue of *E&S*, we invite you to learn along with us.

Yours in discovery,

President

e&S

Engineering & Science

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Editor
Douglas L. Smith

Contributing Editors
Lori Oliwenstein, Kathy Svitil

Contributing Writers
Binti Harvey, Katie Neith, Lori Oliwenstein, Douglas L. Smith, Kathy Svitil, Marcus Y. Woo, David Zobel

Copy Editors
Allie Akmal, Michael Farquhar

Art Director
Jenny K. Somerville

Staff Artist
Lance Hayashida

Design and Layout
Etch Creative

Business Manager
Rosanne Lombardi

The California Institute of Technology
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Contact *E&S* at dsmith@caltech.edu

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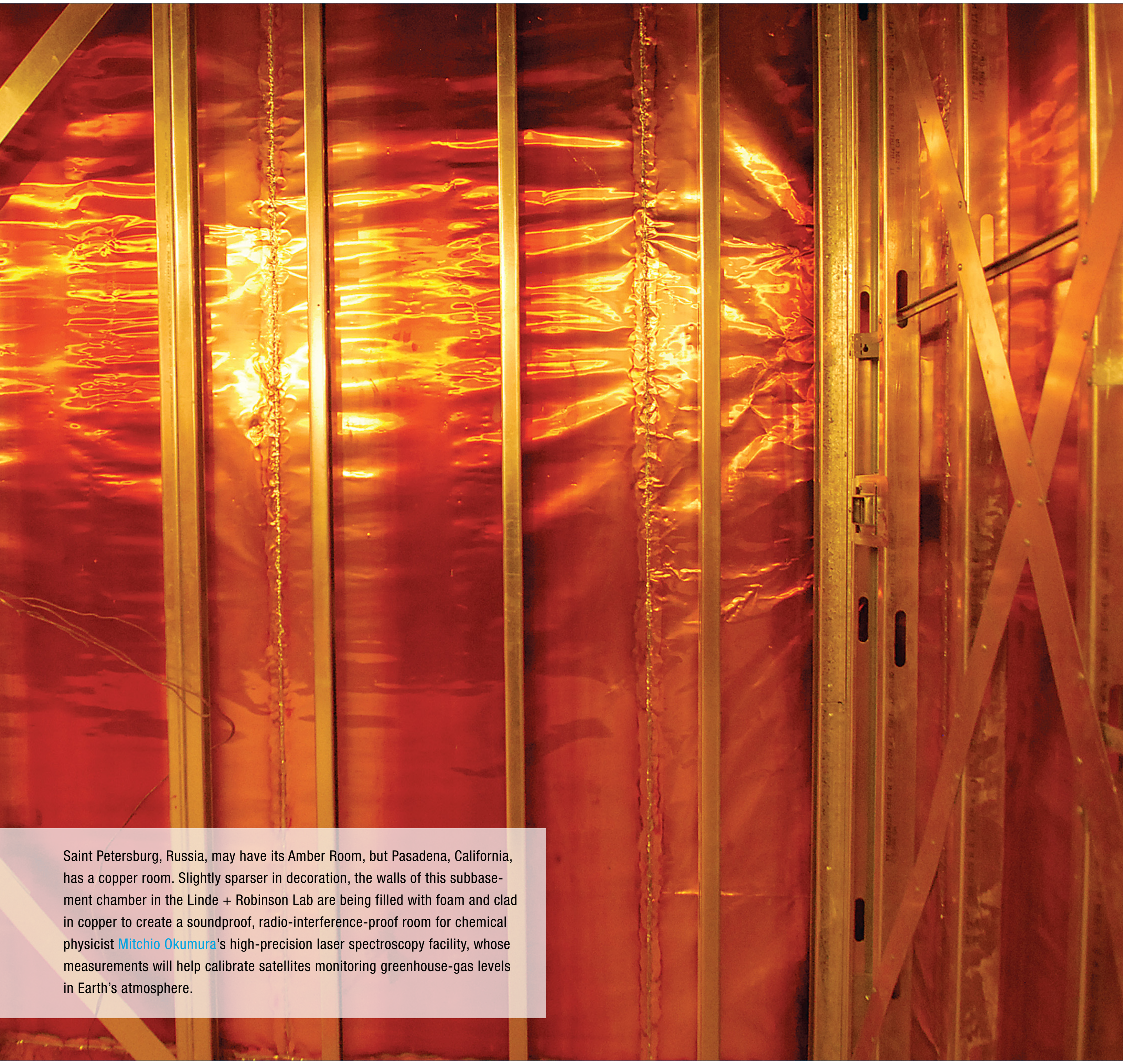
E&S: DIGITAL ARCHIVE

After nearly a decade of labor by summer interns, all of *Engineering & Science* is now available in digital form. You can search for (and download) individual articles by author, title, subject, or year; you can also read each issue cover to cover.

Find it at http://calteches.library.caltech.edu/ The digital archive is in its beta phase, and we invite you to join in the testing. Give it a spin and let us know how it goes—send your comments to dsmith@caltech.edu.

Random Walk



Saint Petersburg, Russia, may have its Amber Room, but Pasadena, California, has a copper room. Slightly sparser in decoration, the walls of this subbasement chamber in the Linde + Robinson Lab are being filled with foam and clad in copper to create a soundproof, radio-interference-proof room for chemical physicist Mitchio Okumura's high-precision laser spectroscopy facility, whose measurements will help calibrate satellites monitoring greenhouse-gas levels in Earth's atmosphere.

DAWN OVER VESTA

At around 10 p.m. Pasadena time on July 15, JPL's Dawn spacecraft slipped into orbit around the giant asteroid Vesta. The spacecraft that was the first to use ion drive—a system that accelerates ions to generate thrust instead of relying on chemical fuels—to boldly go beyond Earth orbit is now the first spacecraft ever to orbit a main-belt asteroid; in a year, Dawn is slated to beome the first spacecraft to leave orbit around a main-belt asteroid and go orbit a second one.

Vesta is 530 kilometers in diameter, and the second most massive object in the asteroid belt. Discovered in 1807, it is thought to be a protoplanet that never quite formed, offering us a look at how a rocky hunk like Earth might have appeared during its infancy.

Dawn will continue to tighten its orbit around Vesta for about three weeks, during which time the navigation team will measure Vesta's gravitational pull in order to make a highly accurate calculation of the asteroid's mass. This will reveal whether Vesta, like Earth, has a nickel-iron core and an olivine mantle—a so-called differentiated interior, which would be a consequence of that interior having once been molten. Meanwhile, the science team will continue its search for possible moons orbiting the asteroid while calibrating the spacecraft's camera and spectrometers. Detailed mapping of Vesta's surface commences in August.

In July 2012, Dawn will restart its ion engine (another first!) and head off to the dwarf planet Ceres, the biggest object in the asteroid belt, arriving in February 2015. —*DS* E&S

This shot of Vesta was taken on July 17 from a distance of about 15,000 kilometers. The resolution is about 1.4 kilometers per pixel.

TÊTE-À-TECH

POP QUIZ: The French word *collisionneur* refers to

(a) a part of a locomotive;
(b) a particle accelerator;
(c) a particularly inept driver;
(d) a part-time Roller Derby jammer.

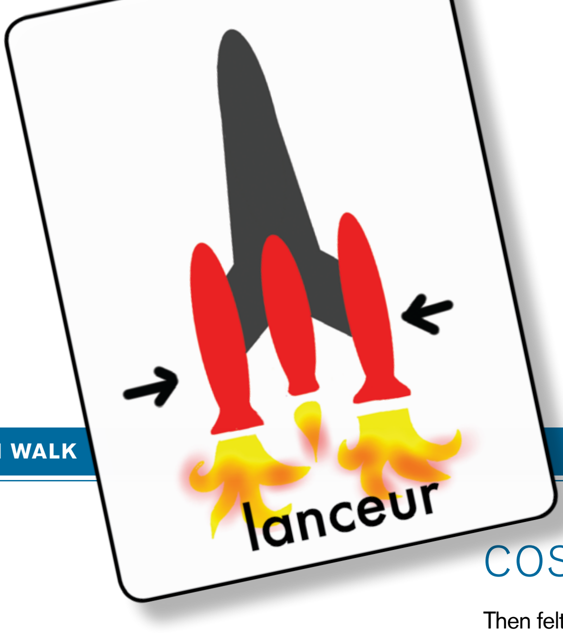
Though it's doubtful you'll ever be called on to provide a precise translation,[1] the same can't be said for Caltech seniors Eva Nichols and Sylvia Sullivan. Both are spending the fall of 2011 in the suburbs of Paris, as exchange students at École Polytechnique. Classes at the elite research institution are conducted entirely in French—and at a level rather higher than the *"J'ai mal aux dents," "C'est la vie,"* or whatever else you might half-remember from high school. Nichols and Sullivan come prepared, however. Earlier this year, they took part in a brand-*nouveau* Caltech language course tailored especially for them: 10 weeks of rigorous immersion in technical French, both spoken and written.

"This isn't a typical conversation course," cautions its creator, Lecturer Christiane Orcel. "There's no 'Have you an unabridged edition of *Les Liaisons Dangereuses?'* or 'Never again shall I order the *pâté*.' We're specifically preparing students to engage in detailed scientific discussions." Lauren Stolper, the director of Caltech's Study Abroad program, explains the course's origins: "Last fall, we had a list of 20 students who had expressed interest in studying at l'École Polytechnique. But at our first informational meeting, only seven showed up." She wondered whether some of the no-shows might have succumbed to doubts *vis-à-vis* their own mastery of the language. Orcel suspected that Stolper's hunch was right: "Americans can sometimes decode French phrases like *une plate-forme pétrolière*,[2] but other technical terms are much more inscrutable. Lauren and I felt that students who were already strong in French could benefit from scientific discussions with native speakers. We brainstormed with Cindy Weinstein, executive officer for the humanities, and then sent a proposal to [Vice Provost] Melany Hunt, who approved funding for a trial term."

And so, twice a week last spring, a handful of students met *en masse* in a Baxter classroom to hear guest lecturers giving technical presentations in French. Each lecture was followed by a Q&A session (naturally, English was *prohibé* in class), and then by a discussion of a scientific article related to the topic *du jour*. Orcel unearthed many of the articles from a journal called *Pour la Science*—the French version of *Scientific American*—but how, so far from Montmartre, Montreux, and Montréal, did she track down lecturers with native or near-native French fluency? "That was the easy part," smiles the native of Nice. "It turns out that we have many, many francophones in the Caltech/JPL community. I just e-mailed every one I knew of. The response was overwhelming."

The makeup of that first class represented an interesting *mélange*: half a dozen undergraduates, one grad student, one postdoc, and a JPL scientist, all of whom met the course prerequisite of two years of French in college or three years in high school. Sullivan, who has been *au fait* with the language since fifth grade, says her newly enlarged vocabulary will come in handy when she's researching ocean sedimentation as part of her studies in France: "I'll be studying in the Département de Mécanique des Fluides, which is a very impressive group. Eventually I'd like to do graduate work in applications of fluid mechanics to environmental questions." And she can, too, since in addition to its undergraduate exchange program, École Polytechnique also conducts a dual master's degree program with Caltech's Graduate Aerospace Laboratories (GALCIT).

Still, a cynic might say, given that English is the *lingua franca*[3] of modern science, isn't knowledge of a foreign language superfluous? *Au contraire*, says Caltech physics professor Harvey Newman[4]: "The predominance of English in scientific discourse is historical fact now. But many of the CERN subcommunities, when they aren't participating in major meetings or multinational working groups, speak among themselves in their



own languages: Italian, German, Russian, Spanish, French. In fact, given the rise of China, Latin America, and other regions, I'm not sure that the exclusive use of English will persist to the same degree over the next few decades."

Will Orcel see an *encore* of her class in the future? It all depends on the funding, she says. Stolper, for her part, is in favor: "This course makes the study of a foreign language truly relevant to Caltech scientists and engineers. It gives them the confidence to put their language training to use in their professional lives." And Newman points out a subtler benefit: "Recalling what it was like to be a student reading original papers and PhD theses in French or German, I think something has been lost. Scientific discourse was once richer in this respect. Anyway, conversing with a scientist in his native language helps build partnerships, friendships, and mutual understanding—all of which are so important in modern life." —*DZ*

---

[1] And if you ever are, the French Ministry of Culture cheerfully directs you to its technical terminology database at http://franceterme.culture.fr.

[2] Oil rig.

[3] Actually, this is Italian.

[4] And researcher at the five-mile-diameter *Grand collisionneur de hadrons* (LHC) at CERN.

COSINE CUISINE

> Then felt I like some watcher of the skies
> When a new planet swims into his ken.
> —John Keats, *On First Looking into Chapman's Homer*

It's a common enough story. Harold McGee (BS '73) majored in English (well, for a Techer that part's not so common), earned his PhD in literature at Yale, and had every intention of spending his life writing about writers (Keats, for one). But as so often happens with creative minds, interests trumped intentions. McGee's perpetual curiosity about what happens when food is cooked—the physics, the chemistry—kept diverting his attention. He soon found himself eschewing Grecian urns and nightingales for double boilers and pheasant under glass.

Today, he's a world-renowned expert on kitchen science, with a monthly column in *The New York Times*, frequent media appearances, and a spot in *Time* magazine's list of "10 ideas that are changing the world." At Caltech, his first book, the encyclopedic *On Food and Cooking*, is the textbook for the perennially popular class PA 16, Cooking Basics. Senior Director of Student Activities and Programs Tom Mannion, who created the course, finds that the book's material resonates strongly with the Institute's undergraduates: "Our students want to know: Why does a soufflé rise? Why does a banana turn black in the refrigerator? What happens to lettuce when you cut it with a knife instead of tearing it? They want to understand all the basics—so that they can create and not copy."

Last May, McGee delivered the keynote address at Caltech's 74th Annual Seminar Day. Over the growing borborygmus of a thousand rapt listeners (it was right before lunchtime, after all), he reviewed four centuries of research in food science: through haute cuisine, nouvelle cuisine, and nueva nouvelle cuisine, right up to the modern era of molecular gastronomy. To hear him tell it, his first scientific contribution to the field of cooking ("practical chemistry," in his words) came rather unexpectedly: "I was reading *Mastering the Art of French Cooking*, where Julia Child recommends using a copper bowl for making meringues and soufflés. She says the copper acidifies the egg white, giving you a better foam. But I remembered enough chemistry to know that copper ions can't change the pH of a protein solution much, so I thought this was just a crazy old cooks' tale."

Months later, he happened across an 18th-century illustration of a French pastry kitchen, featuring (so the caption proclaimed) a boy whipping egg whites—in a copper bowl. Galvanized (McGee, not the bowl), he decided to try the experiment himself, using a spectrophotometer to analyze the resulting foam. He and his coinvestigators, among them Sharon Long (also class of '73, also Blacker House), published their findings in an elegant paper that vindicated Julia while pointing the finger at the metal-binding protein conalbumin. The paper, whose citations include Plato and Boswell, appeared in *Nature*, where "one reviewer said the science was fine—but the subject was fluffy."

The Curious Cook, McGee's second book, might almost be thought of as a culinary lab notebook, taking

Chrome on the Range: While investigating why droplets of frying oil were preferentially attracted to the inside surface of his eyeglasses, McGee created this experimental setup and used it to test a wide (kitchen) range of parameters.

the reader on a happy romp through the world of experimental stovetop physics: boiling points, microwaves, convection, and more. McGee summarized one of his investigations for the Seminar Day audience: "Whenever I fry, I always make a spattery mess all over the place, including on my eyeglasses. But I noticed that most of the oil droplets were ending up not on the outside of the glasses but on the inside. And that didn't make any sense to me."

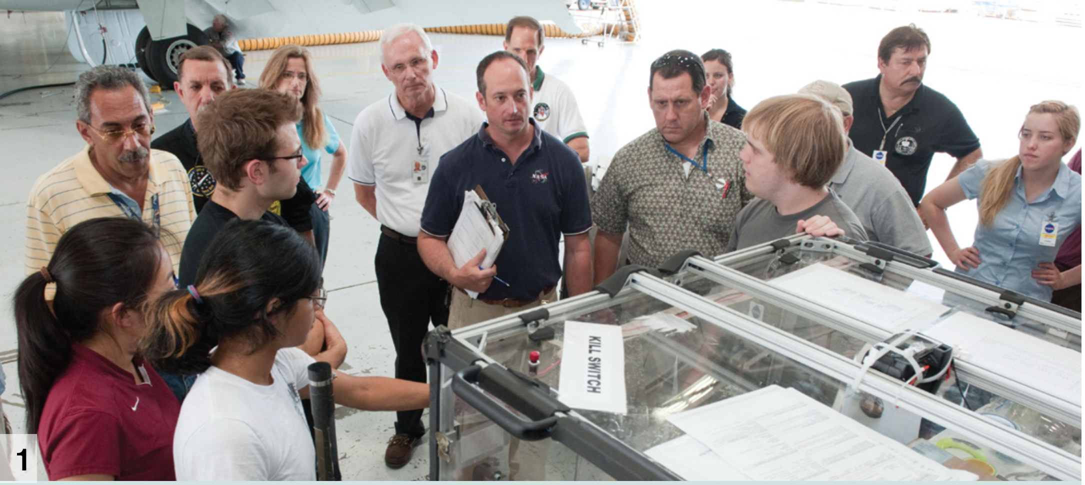
His mind drifted back to Caltech, long affiliated with some Very Famous Oil Droplets Indeed. Was there a link? Were his detouring droplets perhaps being diverted by stray charges of static electricity? "Drawing a connection between kitchen spatter and Millikan's classic experiment was thrilling," he confessed. "I thought maybe there was something funny about the electrical field around the head of a cook. So I made masks out of aluminum foil. I tried grounding myself with a chain. Nothing made a difference—and that really bothered me!"

The explanation, when McGee finally uncovered it, turned out to be more meteorological than electrical. Heated oil, it seems, tends to waft straight up toward the ceiling. As it cools, it rains back down: on the cook's head, on his shoulders, and (since he's bending over the stove) on the upturned—*inner*—surfaces of his downturned glasses. Nor does the traditional billowy white toque favored by chefs block this lipid drizzle, which is why McGee winkingly proposes a new style of fry-cooking headgear: sort of a cross between a stovepipe hat and a baseball cap (think Honest Abe on Opening Day), along with epaulets for aprons.

Last year, McGee received Caltech's Distinguished Alumni Award and also released *Keys to Good Cooking*, a compendium of kitchen tips and tricks. One of its revelations evolved out of an investigation he had performed for *Physics Today* on how often to flip grilled steaks. Analysis preceded experimentation: "I had a friend with a software package for modeling heat transfer in silicon chips, and he modified it for meat. We had the computer simulate different amounts of flipping: once during the cooking, twice during the cooking, right up to once every 15 seconds. The model predicted that the more often you flip, the more even the cross section will be, and the shorter the cooking time." Ever the seeker of empirical evidence, McGee procured some raw steaks and a thermocouple, took them to the grill, and began tirelessly flipping. And? "It worked. It was a wonderful discovery—not the most practical, but it helped us understand how rotisseries work."

KEATS. . . STEAK . . . the anagram may be a little forced, but it nicely sums up Hal McGee's ever-cooking mind.

—DZ e&s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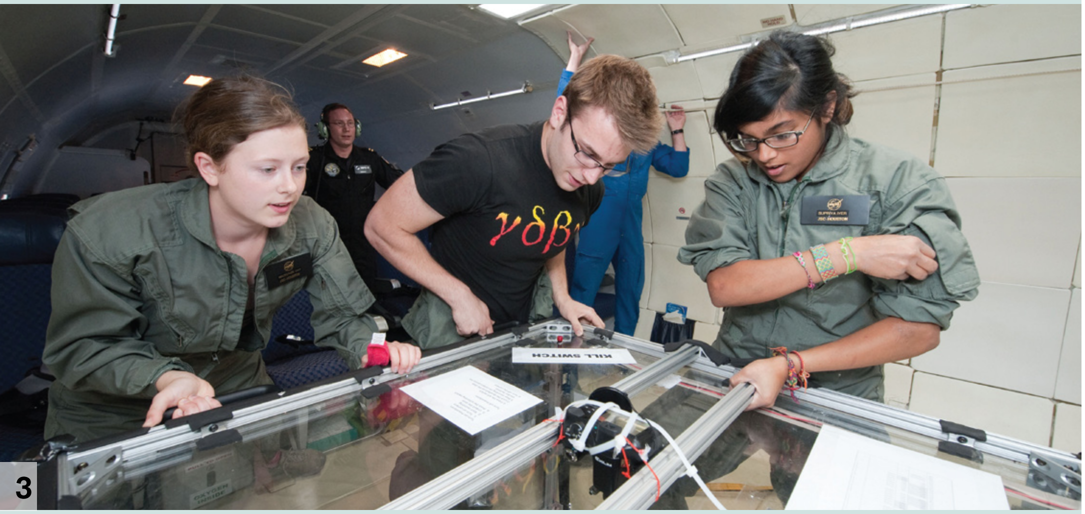
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1 In the final check before boarding, the team explains their project and the operating procedure to the Test Readiness Review committee, which decides if projects are safe to fly.

2 Mackenzie Day, currently a senior studying geology; Colin Ely (BS ’11); and Supriya Iyer, a junior in mechanical engineering, board the first flight of the “vomit comet.”

3 Day, Ely, and Iyer watch a hinge unfold on the first flight.

4 On the second flight, Robert Karol anchors himself with the aluminum and Plexiglas box that houses the experiment as Connie Sun keeps a close eye on the action inside. Both Karol and Sun are seniors in mechanical engineering.


4

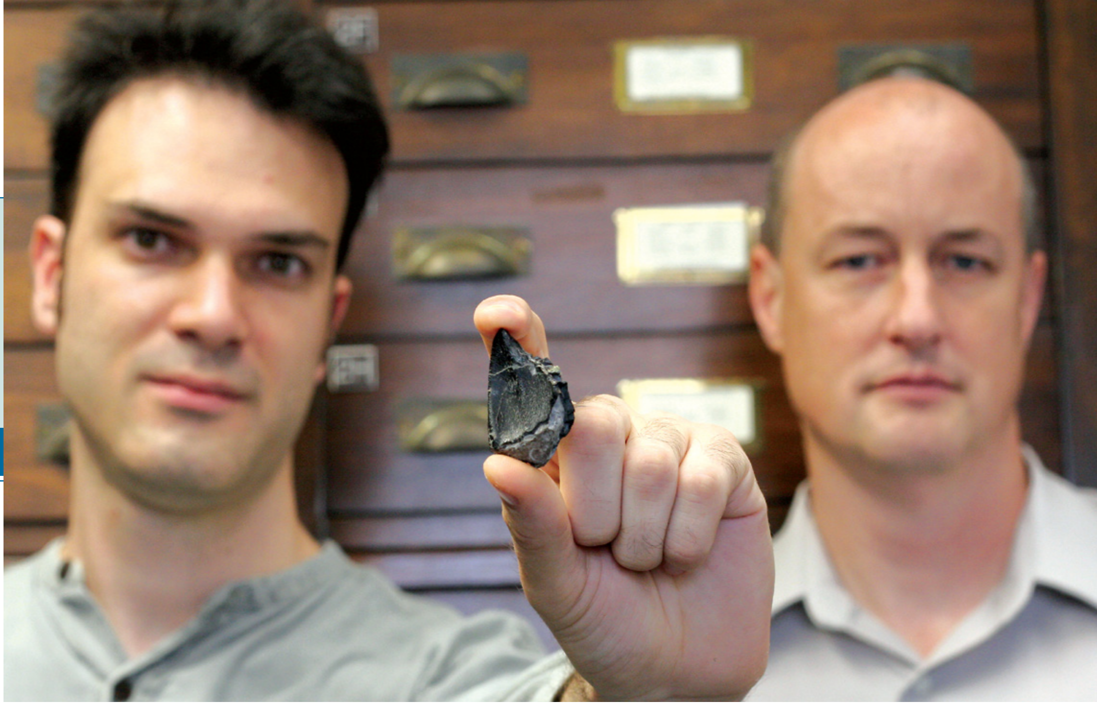

2

FLIGHT OF THE TECHERS

While zero-gravity flights have recently become available to the common person, they are still a distant dream for most of us—unless, of course, you have an extra $5,000 or so to burn. Luckily, Caltech students aren’t common people. In fact, five undergrads got the chance this spring to experience weightlessness at 34,000 feet in the name of science.

During the week of June 6 the team—Mackenzie Day, Colin Ely, Supriya Iyer, Robert Karol, and Connie Sun—tested thin-walled carbon-fiber hinges aboard NASA’s “vomit comet,” a Boeing 727 modified by the Zero Gravity Corporation for microgravity flights. It was the final, exhilarating step in a six-month process in which the students proposed, designed, and fabricated their experiment.

Each team member rode one of two flights high above the Gulf of Mexico, with the flights consisting of 30 parabolas of about 20 seconds of microgravity each. During the flights the students tested how the hinges behaved at different initial angles under various loads (achieved via attached weights) and with different thermal histories. The hinges were designed by grad student Chinthaka Mallikarachchi and fabricated in Caltech’s Space Structures Laboratory, with Sergio Pellegrino, the Kresa Professor of Aeronautics and professor of civil engineering, as faculty advisor. The experiments were recorded via high-speed video cameras for detailed analysis on the ground later.
—KN



Rob Eagle (left) and John Eiler with a new kind of oral thermometer: a dinosaur tooth used to take the creature's temperature.

HOT OR NOT?

Were dinosaurs slow and lumbering, or quick and agile? The answer depends largely on whether they were cold- or warm-blooded. When dinosaurs were first discovered in the mid-19th century, paleontologists thought they were plodding beasts that had to rely on their environments to keep warm, like modern-day reptiles. But in the last few decades several lines of evidence have suggested that they were faster, nimbler creatures, more like the velociraptor stars of *Jurassic Park*. Maintaining such levels of activity in turn implies a warm body whose temperature is self-regulated. But how to know for sure?

New work by a Caltech-led team essentially lets us "stick a thermometer in an animal that has been extinct for 150 million years," says postdoc Robert Eagle, the lead author of the Science paper describing the research. By measuring the levels of rare isotopes in dinosaur teeth, the team has shown that some sauropods—a group that includes the biggest land animals to have ever lived—were about as warm as most modern mammals.

"The consensus was that no one would ever measure dinosaur body temperatures, that it's impossible to do," says coauthor John Eiler, the Sharp Professor of Geology and professor of geochemistry. And yet, using a technique pioneered in Eiler's lab, the team did just that.

The researchers analyzed 11 teeth, dug up in Tanzania, Wyoming, and Oklahoma. Three of the teeth belonged to *Brachiosaurus brancai*, which at some 25 meters from nose to tail tip was as big as the much better-known *Apatosaurus*, a.k.a. *Brontosaurus*. The other eight teeth were from *Camarasaurus*, a smaller creature that averaged some 15 meters long. The results showed that *Brachiosaurus* had a body temperature of about 38°C (100°F) and that *Camarasaurus* was about 36°C (97°F), warmer than crocodiles but cooler than birds.

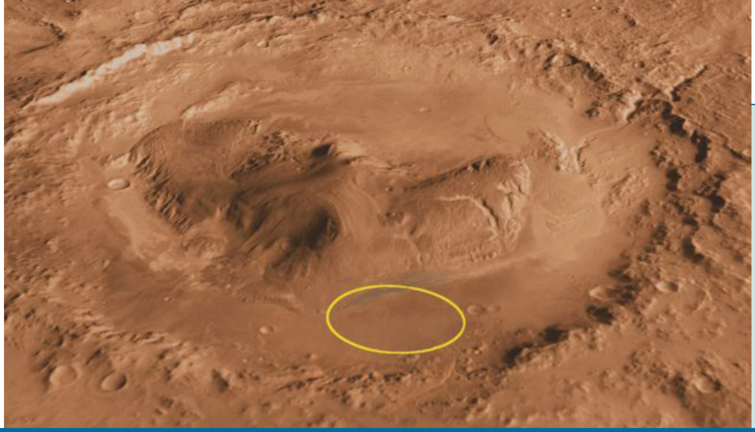
Previous studies of dinosaur metabolism and thus body temperature have, of necessity, consisted of chains of inference—for example, figuring out how fast the creature ran based on the spacing of its footprints, studying predator-to-prey ratios, or measuring the growth rates of bone. But these various lines of evidence were often in conflict. "For any position you take, you can easily find counterexamples," Eiler says. "How an organism budgets its energy—there are no fossil remains for that. You just have to make your best guess based on indirect arguments."

The new method relies on direct measurements of so-called clumped isotopes, eliminating the guesswork. The researchers analyze the concentrations of carbon-13 and oxygen-18 in bioapatite, the mineral that makes teeth hard and bones strong. Carbon-13 and oxygen-18 atoms are heavier than their run-of-the-mill brethren, carbon-12 and oxygen-16. When a carbonate ion (CO_3^{-2}) ion forms in a warm liquid, the heavy and light isotopes intermingle at random; but as the solution cools the heavier isotopes tend to seek one another out. Then, when the carbonate-containing mineral—oh, say bioapatite—precipitates from the liquid—blood, for example—to, perhaps, form the enamel of a tooth, the isotope clumps are locked into the crystal structure to create a permanent record of the temperature of their surroundings, which might be the inside of a dinosaur's mouth.

Eiler says, "What we're doing is thermodynamically based, and thermodynamics, like the laws of gravity, is independent of setting, time, and context." In other words, thermodynamics worked the same way 150 million years ago as it does today. "We're getting at body temperature through a line of reasoning that I think is relatively bulletproof, provided you can find well-preserved samples."

Identifying well-preserved dinosaur teeth was indeed a challenge, and the researchers used several ways to find the best samples. One method compared the bioapatite in the tooth enamel with the more easily altered dentin in the tooth's interior. If both materials had the same concentrations of the heavy isotopes, the odds were that the enamel had been compromised.

So, were the dinosaurs warm-blooded? It's hard to say. Huge sauropods would retain their body heat very efficiently. "If you're an animal that can be approximated as a sphere of meat the size of a room, you can't be cold unless you're dead," Eiler explains. So even if dinosaurs were cold-blooded in the sense that they depended on a sunny afternoon to heat themselves, they could still be warm-bodied—so-called gigantotherms that stay warm through sheer



Gale Crater is at 4.5 degrees south latitude, 137.4 degrees east longitude. The The target ellipse (yellow) is 20 by 25 kilometers. This southward-looking view of the landing site was created by combining images from JPL's Mars Odyssey and Mars Reconnaissance Orbiter with elevation data from JPL's Mars Global Surveyor. The vertical dimension is not exaggerated.

Watch a video of the landing site, narrated by Grotzinger, at http://www.jpl.nasa.gov/video/index.cfm?id=1005

bulk. In fact, some physiological models based on the meat-sphere approximation predict temperatures four to seven degrees higher than those measured. This might be a hint that these dinosaurs had a slower metabolic rate than assumed by the models, which in turn would raise a fresh set of questions.

The team hopes to find out whether body temperature does indeed increase with size by looking at teeth from young sauropods and from adults from species that might only get as big as a St. Bernard. The researchers also intend to take the temperatures of the feathered dinosaurs that gave rise to birds, which may shed light on when warm-bloodedness evolved.

The paper appeared online in the June 23 issue of *Science Express*. The other authors are Thomas Tütken from the University of Bonn, Germany; Caltech undergraduate Taylor Martin; Aradhna Tripati, an assistant professor at UCLA and a visiting researcher in geochemistry at Caltech; Henry Fricke from Colorado College; Melissa Connely from the Tate Geological Museum in Casper, Wyoming; and Richard Cifelli from the University of Oklahoma. Eagle also has a research affiliation with UCLA. The work was supported by the National Science Foundation and the German Research Foundation.—*MW* e&s

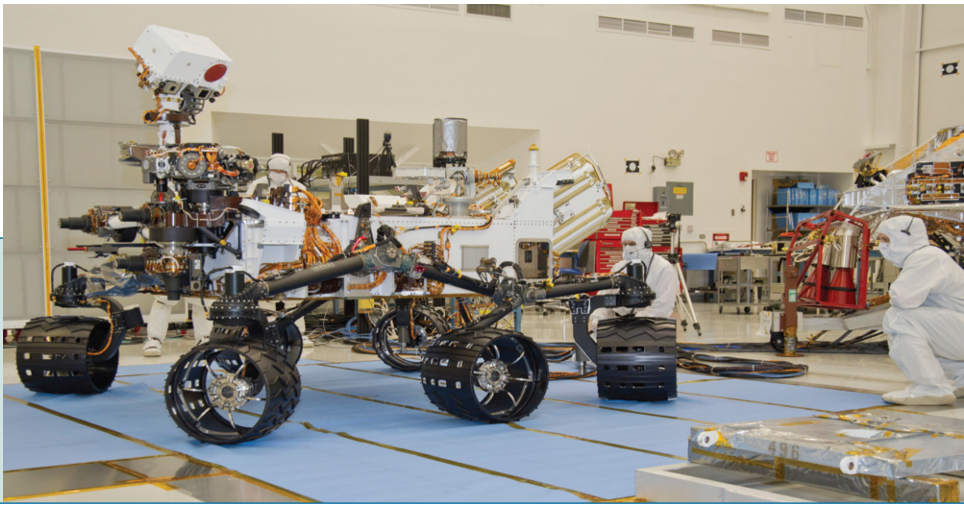
THE CRATER-TO-CANYON TOUR

JPL's latest rover, Curiosity, is now at Cape Canaveral awaiting its November 25 to December 18 launch window. On July 22, NASA announced its destination: Gale Crater, 154 kilometers in diameter (about the combined area of Connecticut and Rhode Island) and with an imposing central mountain five kilometers tall that looms higher over the crater floor than Mount Rainier does over Seattle. The plan is to set the rover down on an alluvial fan formed of loose material washed down from the crater walls. After studying the soil, Curiosity should be able to drive to the mountain, whose lowest layers contain clay minerals and sulfate salts usually formed in wet conditions on Earth. "Gale Crater is very low," says John Grotzinger, the Fletcher Jones Professor of Geology and Curiosity's project scientist. "It's a place where water might have pooled and formed lakes."

And where there was water, there may have been life; if microbes once flourished there, they may have left organic molecules behind. Unlike its predecessors, Sojourner, Spirit, and Opportunity, Curiosity is equipped with a mass spectrometer, a gas chromatograph, and a tunable laser spectrometer, all for detecting these molecules.

A canyon cuts deep into the mountain; as Curiosity trundles up the sloping canyon floor, rock layers representing tens or even hundreds of millions of years of Martian history will be exposed to its view. Curiosity's primary mission will last one Martian year, or very nearly two Earth years, during which Earthbound scientists will be able to chronicle unprecedented eons of environmental change on our sister planet.

After the primary mission ends, Grotzinger hopes Curiosity will climb to a region of lighter-colored rocks near the top of the mountain. These rocks appear to be very soft and easily eroded by the wind, unlike the rock layers lower down, and their composition is a mystery; if Curiosity can make it that far, the rover will be able to determine their makeup and possibly their origin. —*DS* e&s



On June 3, Curiosity was still in the JPL clean room where it was built, undergoing some final tests before being shipped to Cape Canaveral.

Many scientists, including Eileen Stansbery of the Johnson Space Center, spent weeks in a set of clean rooms extracting the shards of the shattered solar-wind collection plates from Genesis's mangled remains.

AND THE EARTH WAS WITHOUT FORM . . .

Scientists have found that the sun is different from the earth—no, really! You see, the sun and the planets all condensed out of roiling clouds of dust and gas that were presumably well stirred—and should therefore have been the same throughout—so these differences contain important clues as to how the solar system came to be, says emeritus professor of nuclear geochemistry Don Burnett. Burnett is the principal investigator for NASA's Genesis mission, which returned samples of the solar wind to Earth in 2004. The solar wind is a high-speed stream of charged particles "blown" from the sun's outer layers, which are believed to be a fossil remnant of that primordial solar nebula.

The work was done by two teams, both of which included Burnett. One team, led by Kevin McKeegan of UCLA, analyzed the samples' oxygen levels. The other team, led by Bernard Marty from the Centre de Recherches Pétrographiques et Géochimiques at Nancy, France, looked at nitrogen levels. The results appeared in companion papers in the June 24 issue of *Science*.

Atoms of oxygen and nitrogen come in various forms, called isotopes, which differ in the number of neutrons they contain; these isotopes are chemically identical but have different masses. In both cases, the researchers found that the solar samples had fewer atoms of the heavier isotopes than does Earth.

Oxygen, for example, is the third most common element in the sun, and the chief component—in the form of silicon and other oxides—of the rocky planets. Oxygen-16 is the usual isotope, but Earth rocks, moon rocks, and rocky meteorites all have significant traces of the heavier oxygen-17 and oxygen-18, and the ratios of the isotopes are all roughly consistent, regardless of the rock's origin. The ratio of oxygen-18 to oxygen-16 in the solar-wind samples, on the other hand, is about 7 percent less.

Nitrogen is the fifth most common element in the sun, and makes up about 78 percent of Earth's atmosphere. The ratio of nitrogen-15 to nitrogen-14 in the sun proved to be roughly 40 percent less than in our atmosphere. Giant gasbag Jupiter, however, appears to have the same nitrogen-isotope ratio as the sun.

As the solar system formed, the sun would have condensed first, from the thickest part of the cloud, leaving a thin disk of material around itself like the rings around Saturn. One popular explanation for the different isotope ratios holds that, as the sun began shining outward onto the disk, the ultraviolet light capable of breaking up molecules of carbon monoxide containing oxygen-16 got absorbed near the disk's surface. Meanwhile, the wavelengths able to dissociate the heavier isotopes penetrated more deeply, releasing oxygen-17 and oxygen-18 into the materials that would form the inner solar system. Alternatively, the heavier isotopes might have already sought out the dustier regions that would become rocky bodies—which then, of course, raises the question of how *that* happened.

Genesis, launched in August 2001, spent 886 days collecting solar-wind samples at Earth's L1 Lagrange point—a locale about a million miles to the sunward side of Earth, where the two bodies' gravitational forces balance. On September 8, 2004, the spacecraft's sample-return capsule came to rest in the Utah desert after executing what might euphemistically be described as a geobraking maneuver when the parachute failed to deploy. But, as Burnett told *E&S* in 2007, "We went out and picked up the pieces. You couldn't destroy the atoms in the crash—the only thing you can do is contaminate them." Almost a decade invested in salvaging, sorting, and decontaminating the samples is now starting to pay off. —*DS* E&S

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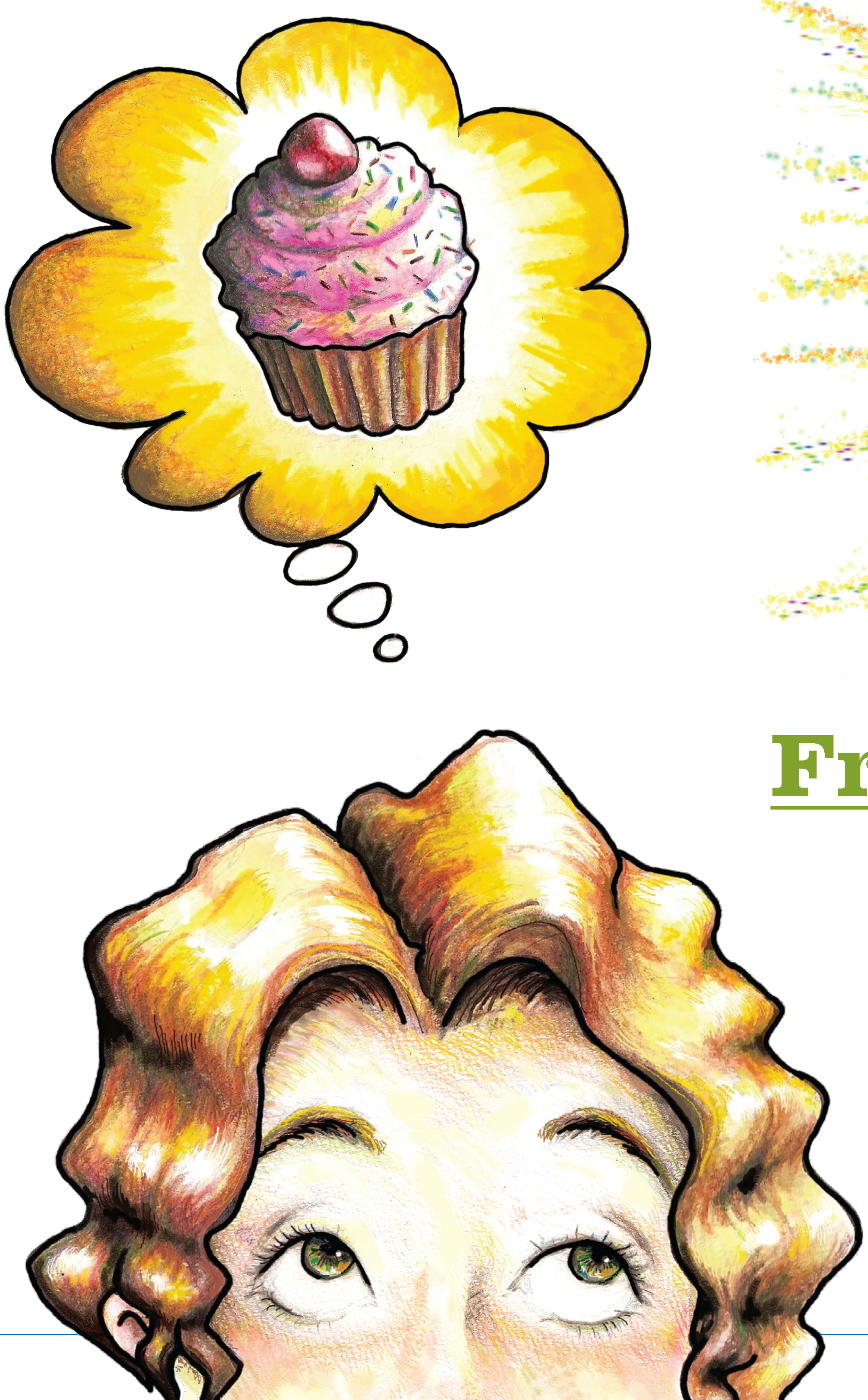

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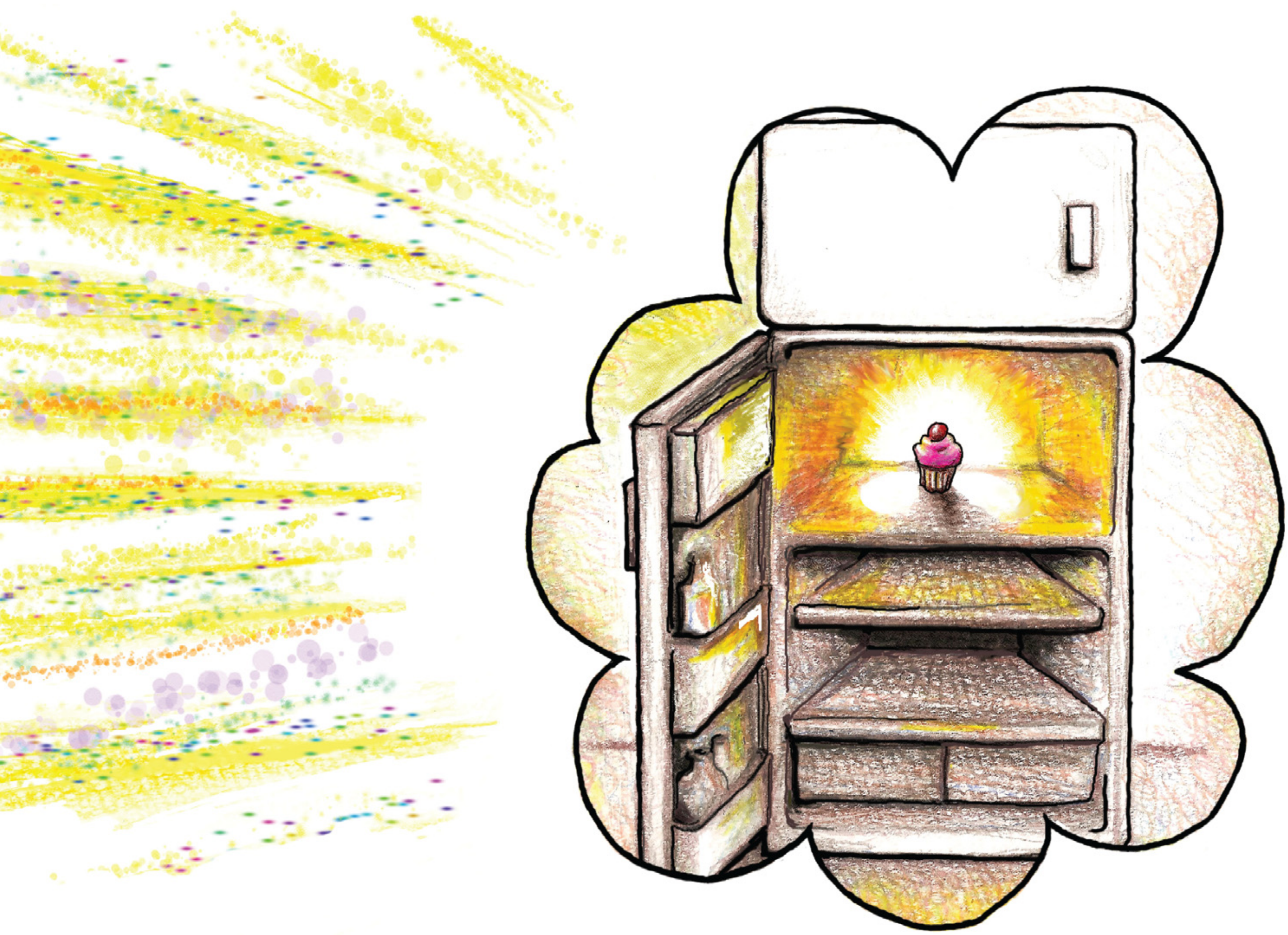


Dendrites to Decisions

By Lori Oliwenstein

The average human brain—weighing in at a scant three pounds—has, according to one estimate, upward of 100 billion neurons that connect with one another via some 100 trillion synapses.

A hundred trillion? Wow. You learn something new every day, right?

But wait. Was that really learning? Or was it just a bit of trivia you're likely to forget as quickly as you read it? What, exactly, *is* learning?

Ah, there's the rub—or, if you will, the learning curve—says psychologist John O'Doherty, one of the dozen or so Caltech faculty for whom learning about learning has become a scientific endeavor.

"There are lots of ways to talk about learning," he says. "The brain is always learning. It's key to our survival; we need to learn how to find things like food, water, and shelter. Equally, if not more importantly, we need to learn to avoid bad things, like getting run over by a car or being eaten by a mountain lion."

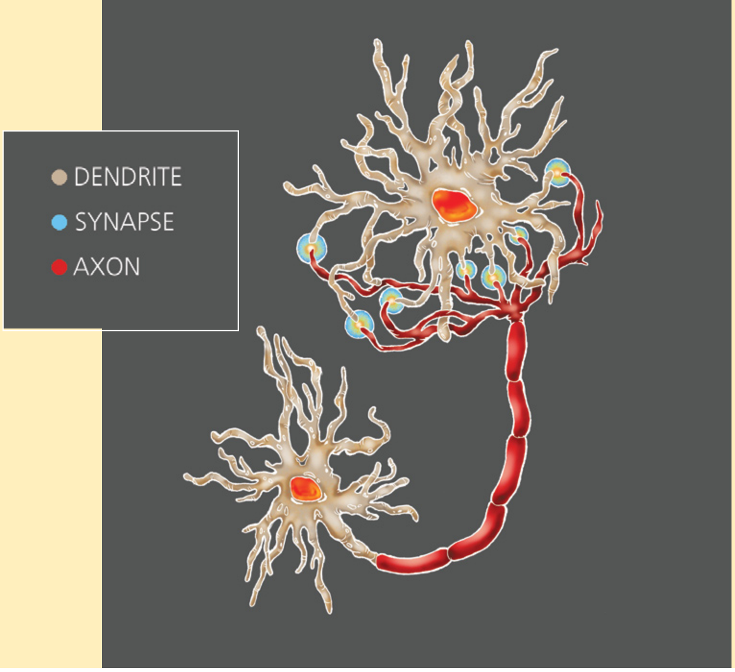
Biologist Thanos Siapas sees learning as part and parcel of memory, upon which his research focuses. "Learning and memory are two sides of the same coin," Siapas notes.

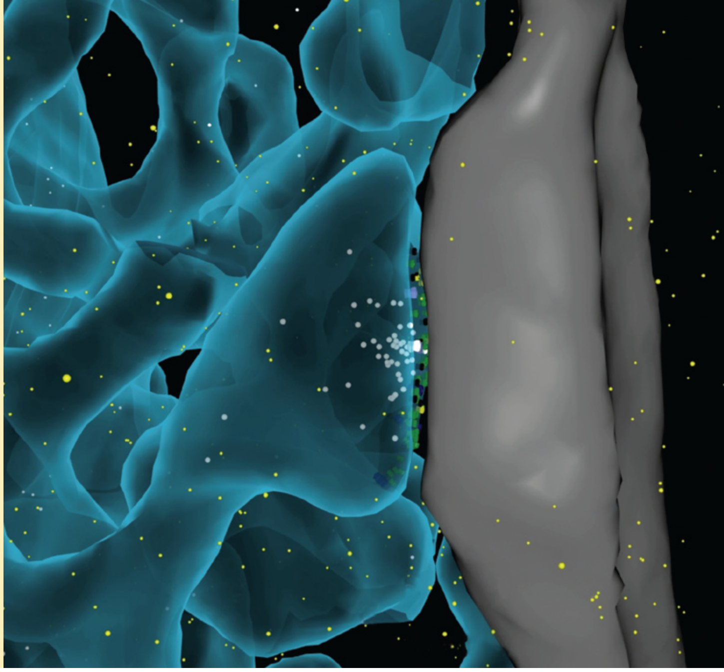
Behavioral economist Colin Camerer, on the other hand, sees learning as just another kind of decision making—a process of assigning values to objects and experiences and thus "learning" about them, and about whether you'd want to make the same choices in the future.

And if you ask Mary Kennedy, who has spent the last 30 years taking apart and exploring the inner workings of the brain's synapses, you'll get yet another take. "Learning is essentially a form of neural plasticity," she says—the ability of individual brain cells to make new connections or retune those that already exist.

LEARNING TO CHANGE

A synaptic connection has three parts: the sending neuron's axon, the receiving neuron's dendrite, and the cleft in be-





tween where axon and dendrite almost, but don't quite, touch. In an amazing feat of sleight of hand (sleight of synapse?), an electrical impulse reaching the axon's tip is transformed into a burst of chemicals that cross the synaptic cleft, only to be changed back to an electrical impulse again in the dendrite. This impulse then travels down the dendrite, through the neuron's cell body, and out along the axon to another set of synapses.

Not all synapses are created equal, however. Although each neuron has thousands of synapses, most of them are small and weak, and have little if any influence on the next nerve cell in line. Learning something new—opening the lines of communication between neurons that previously wanted nothing to do with one another—requires pumping up the volume in the synapses connecting them, so that the intended message comes through loud and clear.

It is this volume adjustment that Kennedy studies in the most minuscule detail. Specifically, hers is one of a handful of laboratories in the world that focus on what is known as the postsynaptic density, or PSD. The PSD, as the name implies, is at the receiving end of the synapse—it's that part of the dendrite that includes the cell membrane and the area just beneath, where the chemical signal is plucked from the cleft and converted back to electrical form.

Recreating the electrical impulse in the dendrite requires an influx of ions—and calcium, Kennedy says, does a memory good. The intercellular soup in the synaptic cleft is heavily seasoned with calcium ions, and the surface of the PSD is studded with proteins called NMDA receptors that, when activated, open to let calcium ions into the dendrite.

It's an almost impossibly complex process, but it all comes down to this: The more calcium that comes into a dendrite through the NMDA receptors, the more that dendrite's internal skeleton branches and expands. The more the skeleton branches, the more the PSD's membrane sprouts another kind of receptor—called an AMPA receptor—that ultimately causes the neuron to fire.

And all of that—the influxing of calcium, the expanding of the skeleton, the adding of AMPA receptors—is what defines neural plasticity.

"Neurons that fire together wire together," Kennedy quips. But it's no joke: That calcium cascade tightens and strengthens the connections between neurons. Without that cascade—without a robust, well-connected PSD—learning comes to a screeching halt.

"When I started at Caltech 30 years ago," says Kennedy, "we didn't know any of the molecules in the postsynaptic density; none of them. We knew it as a dark thing that we saw in the electron microscope. Now we know most of the proteins that are there, and we know quite a bit about how they work and how they respond to calcium."

Having dissected the PSD and identified its components, Kennedy's group is now trying to figure out the system's dynamics. "We want to try to understand how subtle differences in calcium flux lead to strengthened synapses—or, sometimes, to weakened ones," she says. "The precise pattern of calcium flux into the synapse is what controls whether it strengthens or weakens; it's at the core of what happens during neuroplasticity. And yet, nobody really knows how it works."

REMEMBERING TO LEARN

What we do know is that learning is an oh-so-deliberate process, a sweat-and-tears and all-night-problem-set endeavor. In other words, learning takes time, says Thanos Siapas.

Siapas studies just how the brain takes incoming information, shunts it around, and finally lays it down in ways that will allow it to be retrieved quickly and easily at a later date—that will allow the information to be remembered, to be learned.

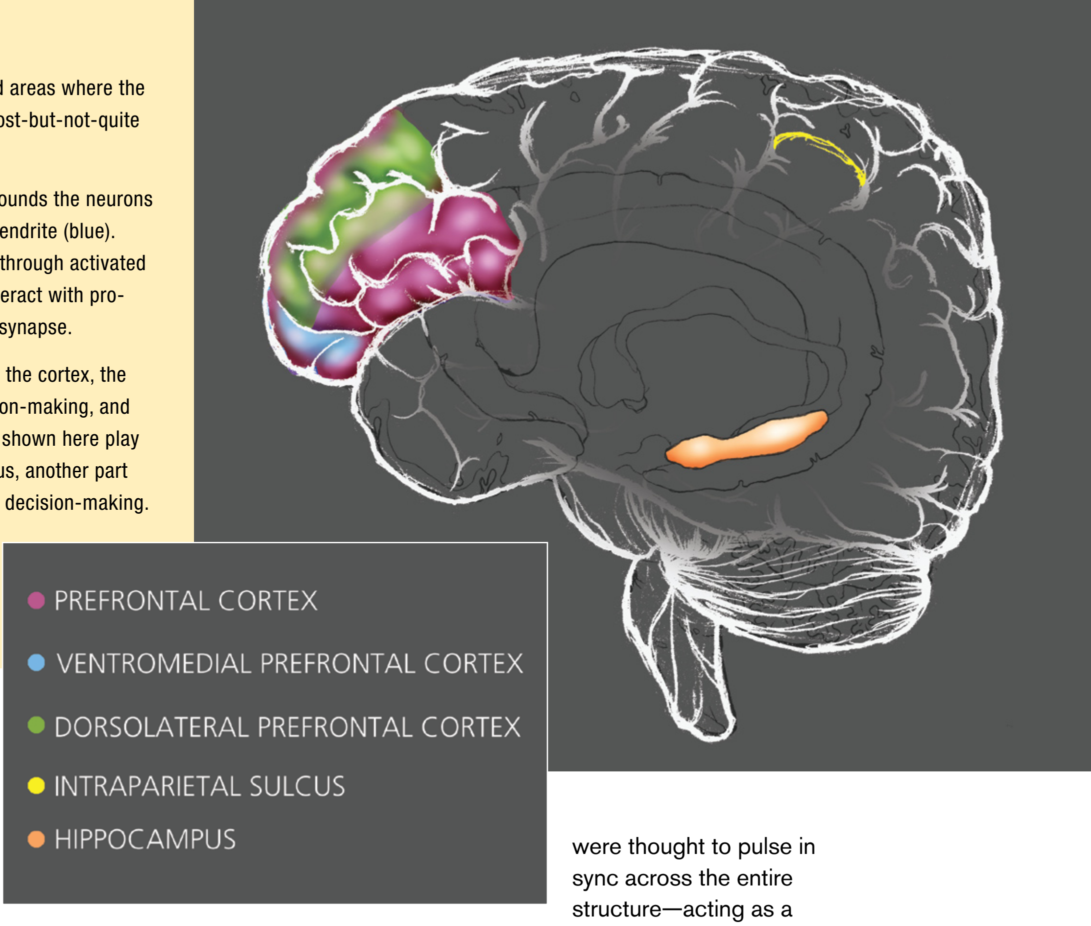
"It's a process," says Siapas. "When you learn something, your brain continues to make changes for a long time after. You can't just store a new memory; you need to integrate it with the other things you already know. And that's much trickier than you might think."

While Kennedy and her group are peeking inside individual neurons, Siapas and his colleagues are taking a

Far left: The brain's synapses lie in the blue-encircled areas where the branching tips of the sending cell's axon (in red) almost-but-not-quite meet the receiving cell's dendrites.

Left: Calcium ions are dissolved in the soup that surrounds the neurons and fills the synaptic cleft between axon (gray) and dendrite (blue). Here, calcium ions (the clustered white specks) rush through activated NMDA receptors into the dendrite, where they will interact with proteins in the postsynaptic fluid to help strengthen the synapse.

Right: The prefrontal cortex, outlined in red, is part of the cortex, the brain's outer layer, and is involved in planning, decision-making, and other higher-order functions; the two major subparts shown here play roles in goal-directed learning. The intraparietal sulcus, another part of the cortex, also contributes to action-planning and decision-making. The hippocampus, which helps process memories for storage, is buried deep in the brain's interior.



step back to look at large conglomerations of brain cells and their relationships with one another. At the center of consideration is the hippocampus, a curved ridge of gray matter known to be essential for learning and memory formation—though it is not, Siapas points out, where those memories are ultimately stored.

"The hippocampus helps establish memories, helps consolidate them," he says. "But it consolidates them somewhere else. We want to understand how the hippocampus is activated during learning, and how it communicates with other brain areas during this process."

To do that, Siapas says, requires monitoring many brain areas over long periods of time. "We're talking about months or even years in humans, weeks in mice," he notes.

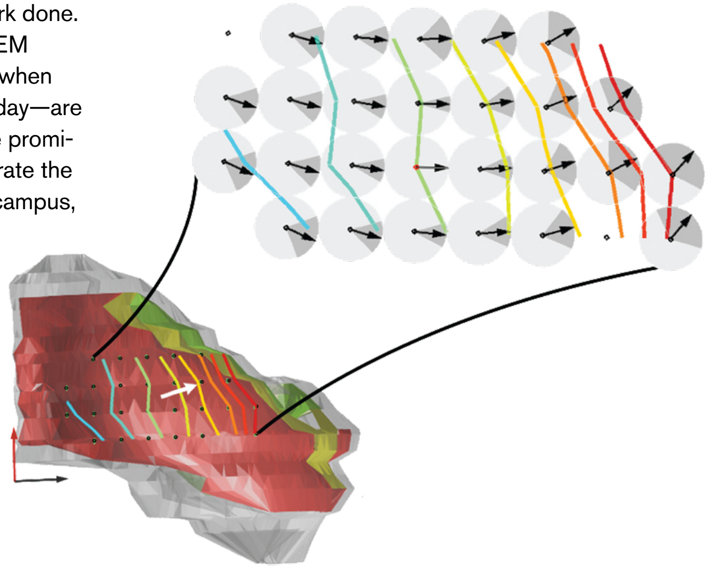
But that long-term effort has paid off. For instance, using high-tech recording and computational techniques, Siapas and Casimir Wierzynski (PhD '09), now a postdoctoral scholar, were able to pinpoint a number of synchronized neuron pairs in which a hippocampal neuron's firing was followed within milliseconds by the firing of a neuron in the prefrontal cortex.

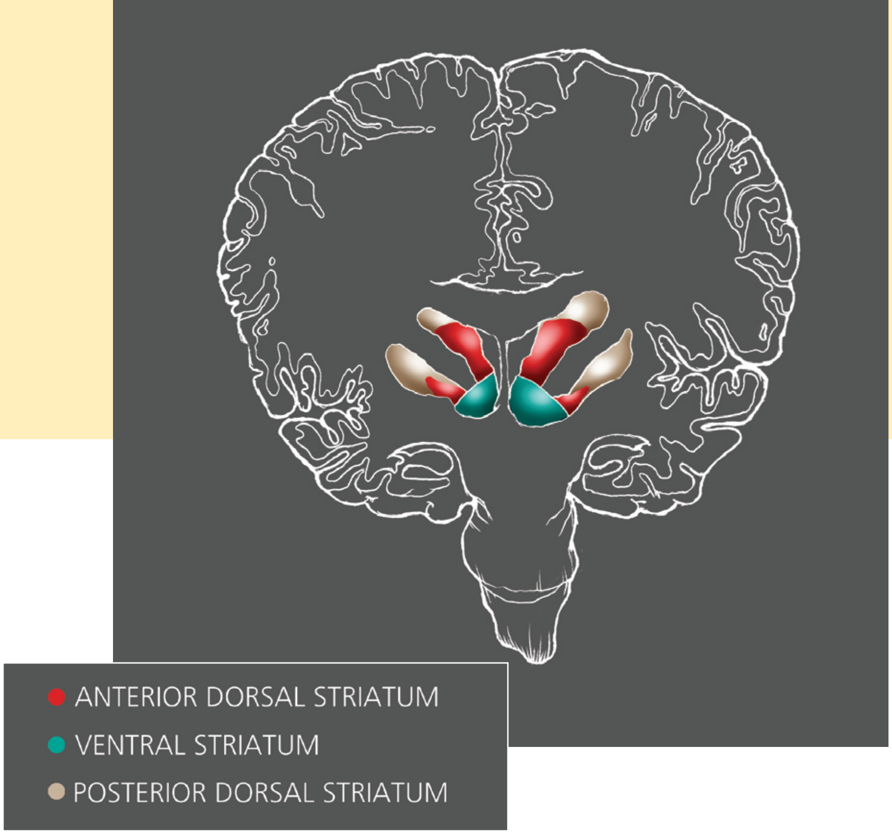
"This is exactly the kind of relationship that would be needed for the hippocampus to effect changes in the neocortex—such as the consolidation, or laying down, of memories," says Wierzynski, who was the lead author on the 2009 *Neuron* paper reporting the work.

The scientists also found that these bursts of neuronal chatter happen only during slow-wave sleep—the deep, dreamless portion of your night's rest. During the dream-laden periods of REM sleep, it seems, you may well be too busy fighting zombies or wandering naked through your high-school hallways to get much real brain work done.

But what *do* kick in during REM sleep, Siapas says—as well as when we're up and about during the day—are the theta oscillations. These are prominent brain rhythms that orchestrate the activity of neurons in the hippocampus, and for decades they were thought to pulse in sync across the entire structure—acting as a master clock, a centralized pacemaker. It wasn't until postdoc Eugene Lubenov, now a senior research fellow, and Siapas took a more detailed look at these biological cadences that the pacemaker paradigm was dealt its death blow. It turns out instead that theta oscillations sweep across the hippocampus in a traveling wave, moving steadily from one end of the structure to the other. "In other words," says Siapas, "the hippocampus has a series of local time zones, just like the earth has."

Lubenov and Siapas showed that brain rhythms called theta oscillations move across the hippocampus in waves. In this diagram, each colored line represents a "time zone" in which the oscillations are in sync, as shown by the clock hands in the inset.





The striatum, buried deep in the brain, takes inputs from various parts of the cortex. The anterior dorsal striatum (red) receives inputs from the ventromedial prefrontal cortex and is part of a circuit for goal-directed learning. Both model-free learning, which is learning without a map, and fictive learning, which is learning from what others do, involve the ventral striatum (green). Meanwhile, the posterior dorsolateral striatum (tan) controls habitual behaviors.

DECIDING TO LEARN

Learning may be a slow-and-steady turtle of a process, but at its inception, it can be a hare-like burst of action that begets an unexpected response—a fleeting meeting of instinct and serendipity.

The most basic of instincts—flinching at a really loud noise, wincing in pain when you stub a toe—are reflexive rather than learned, notes psychologist John O'Doherty. But everything above that level involves some form of knowledge acquisition.

"Learning comes in even when you're talking about Pavlovian conditioning," O'Doherty says. "It's one of the most basic forms of learning—associating a cue like a buzzer in the lab with food, or a rustling in the bushes with a mountain lion. We *learn* to associate those cues with something significant, and then to respond physiologically to the cue—to salivate even before we see the food, or to feel a fear-based rush of adrenaline before the bushes part and the lion is upon us. By learning to anticipate significant events based on past experience, we buy ourselves time so that we're better prepared to eat, or fight, or flee, or whatever the appropriate action is."

We kick it up a notch when we learn how to interact with our environment and make things happen to suit ourselves—the so-called instrumental conditioning that drives mice to push a lever to get food, or tells us to shake a tree to make the fruit fall down. We've learned that an action will give us what we want, and we go for it.

In general, O'Doherty says, instrumental conditioning can be divvied up into two general categories: habit learning and goal-directed learning.

Imagine you're a toddler walking past the refrigerator. For absolutely no reason, without giving it a second (or first) thought, you open the door. And there, in a spot of fridge-lit glory, sits a single, perfectly frosted cupcake. You grab it—of course you do—and eat it. The moment you stuff that cakey goodness into your mouth, you will have learned something: opening a fridge door can have positive consequences. "And the next time you walk past a refrigerator," O'Doherty notes, "you're much more likely to open it."

That, in a nutshell, is habit learning.

Goal-directed learning, on the other hand, is a tad more sophisticated, and less dependent on dumb luck. "You're thinking about the consequences of taking a particular action," says O'Doherty. "You think, 'I want a cupcake. Where would it be? Ah, let me try the fridge.'" Rather than just opening random dresser drawers or your toy box, you stop before you act, before you waste your energy, and evaluate the possible outcomes.

And this, he notes, can motivate less physical actions as well. It's goal-directed learning that tells you to sit down and study for a test, because you're more likely to get a positive result—a good grade—than if you blow it off. No gold star or Saturday-night use of the car on the line? No real reason to pick up that textbook.

"Habits are things we do without thinking of the consequences," O'Doherty says. Being goal-directed, on the other hand, is all about reaping what you sow.

Which is not to say that goals and habits aren't linked. In fact, they are—intimately so, in many cases. Take bike riding. When you first get on a bike, you are completely goal-directed; you have to think about every movement your body makes in an attempt to keep yourself upright. But, after a while, you don't have to think any more. Your responses become habitual, reflexive.

Sounds obvious, right? And yet it was only in the last couple of years that O'Doherty, postdoc Elizabeth Tricomi (now an assistant professor at Rutgers), and Bernard Balleine at UCLA actually showed experimentally that—over time and with training—goal-directed behavior in humans can indeed become habit.

"People had skirted around the issue before then," O'Doherty admits. "They'd assumed certain behaviors were habitual. But no one had actually done what we did."

In addition, the scientists were able to pinpoint, for the first time, the control of habitual behavior to a specific area of the brain—the posterior dorsal striatum.

O'Doherty says such insights are critical. "We want to know which parts of the brain are involved in learning, and what are the algorithms—what programs does the brain run—to allow these different kinds of learning to take place," he says. And the only way to get those sorts of insights is to actually watch the brain at work.

In the functional magnetic resonance imaging (fMRI) machine at Caltech's Brain Imaging Center, almost any type of mental gymnastics is fair game. This fMRI is the same sort of whole-body scanner that an orthopedist might put you in to look for a torn ligament; here, the volunteer lying in the machine performs a predefined task—placing a bet, for example—and as the thought process unfolds, the scanner tracks the brain's active areas in 3-D. Says O'Doherty, "Not only can we identify what parts of the brain are active when, we can also figure out what algorithms are being implemented when you do one task or another."

Caltech-led fMRI studies have confirmed that goal-directed learning tends to begin in a part of the brain just above your eyeballs called the ventromedial prefrontal cortex (VMPFC); this is the area made famous by railway worker Phineas Gage in the mid-1800s, when a large iron rod pierced his brain and robbed him of his decision-making and social skills. The VMPFC, says O'Doherty, talks to a region in the center of the brain called the anterior dorsal striatum. Eventually, control of the behavior in question passes to the posterior dorsal striatum, which is closely connected to the motor cortex and thus plays a larger role in habit learning than it does in the thinking-things-through process of goal-directed learning. At this point, what used to require mental effort is starting to go on autopilot.

Learning typically involves updating your expectations continuously as things change around you, applying what you've learned in the past to figure out what to do in the future. You might look at what the stock market did around this time last year, for instance, before deciding whether to throw a little extra money into your portfolio now.

Such updates are, obviously, nothing more than approximations and bound to fall short. Indeed, there's a name for that shortfall: prediction error. It's the difference between what you think you'll make in the stock market this year, and what you actually do make. The neat thing about learning is that, next year, you can use that new info to change your expectations again and perhaps reduce your prediction error. "When you've completely 'learned' something," notes O'Doherty, "your prediction error goes down to zero."

This sort of trial and error is called model-free reinforcement learning and may explain what goes on when you are starting to form a habit. But there's another strategy: model-based learning.

Explains O'Doherty, "If we're sitting here in my office on the third floor, and I tell you, 'I left $10,000 down in the lobby, and I've told five other people about it,' the only way you can get to that money before they do is to create a map of the building in your brain and compute the value of taking different routes. Chess is the same way; in order to reach your goal, you need to learn how to map out your particular situation."

This, then, is a kind of goal-directed learning. Going after the cash without

a map in mind would be a total bust. You'd just wander down corridor after corridor, aimlessly; those other guys would be out spending the loot before you even found the stairs.

In a Neuron paper last year, O'Doherty and then-postdoc Jan Gläscher described how these two modes of learning interact to help us make critical decisions, and showed that they actually involve different brain areas. Model-free learning was found to involve parts of the striatum including the ventral striatum, while certain aspects of the model-based learning system were found to depend on some areas in the cerebral cortex—the intraparietal sulcus and the dorsolateral prefrontal cortex. "The cortical areas are learning the map that you are going to need in order to perform goal-directed learning," O'Doherty explains. The complete mechanism, of course, is much more complicated. "There is a considerable network of brain areas likely contributing to each of these learning processes."

Learning modes vary over time—with bike riding starting as a goal-directed activity, but later becoming a much less "computationally expensive" habit—and even from moment to moment. In a study published earlier this year, O'Doherty and postdoc Ryan Jessup looked at the gambling strategies used by 31 volunteers playing a roulette-type game (talk about expensive!) while in the fMRI machine. The game involved betting on which of three colors would come up next on a three-colored wheel, but there was a twist—the three regions were of unequal size, and the sizes changed with each spin.

Two radically different approaches quickly emerged. Sometimes players relied on reinforcement learning, a version of model-free learning in which they picked a "lucky" color that had paid off in the past. If the streak turned cold, they'd switch to the "gambler's fallacy"—a more model-based strategy based on the belief that one color was "due," either because it hadn't come up in a while, or because the spins seemed to be following a specific pattern.

The different strategies were reflected in the subjects' brain activity, says Jessup. The dorsal striatum flickered to life when participants were using model-free reinforcement learning—the ones who wagered based on what had worked for them previously—but stayed relatively quiet when bettors were under the sway of the model-based gambler's fallacy.

As it turns out, neither of these strategies is particularly good for this particular game. At the beginning of every experiment, the subjects were explicitly told that the computer was picking winners at random, and that the odds of a color hitting were proportional to the area it occupied. The best bet would thus be the color taking up the biggest piece of the wheel on that spin, regardless of what that color happened to be. Says O'Doherty, "The fact that we repeatedly choose less-promising strategies in the face of a more rational alternative tells us that these learning processes are so deeply ingrained in our brains that they can influence our behavior even in situations where it is actually counterproductive."

THE ACTION NOT TAKEN

But how do you make decisions when you can't bring much to the table in the way of personal experience? How do you assess the roads not taken?

"When you have a set of potential actions—like which movie to see—you learn only about the movie you choose," says behavioral economist Colin Camerer. If the chosen flick was exceptional, the next time there's a movie starring that same actress, you'll be more likely to see it; you'll have learned something from the experience. Similarly, if the movie was awful, you'll know what to do the next time you're considering an offering from that particular director.

As for the movies you passed up? "It would be useful to have a mechanism to learn more about them, too," notes Camerer.

And you do: it's called fictive learning, or learning from the what-ifs of life. In other words, you *can* learn from other peoples' experiences. In the case of the multiplex, you can ask friends who saw the other movies what they thought, and then incorporate those opinions into your worldview for future decision making.

Camerer and colleagues have explored fictive learning in a series of experiments, the most recent involving a game in which 54 volunteers made a series of "investments." At the end of each round, the results of all the investments were revealed to all the players.

The fMRI revealed that processing "rewards not received from actions not taken" happens in the ventral striatum, the same brain area where model-free learning occurs. "We see signals about what you could have done in regions similar to those that encode signals for actual rewards," Camerer remarks. And so, if your friend raves about the movie you didn't see, your brain will tuck that information away in the same place where it normally sticks the information about movies you yourself saw and enjoyed.

There is, however, a slight catch: some of Camerer's earlier studies have found that the weight you give to a fictive account of something's value is about half what it would have been if you'd learned about it yourself.

Which means that the next time you check your local cinema's listings, you're still likely to snub *The Hangover Part II* if you hated Part I—no matter how many times Uncle Joe insists you absolutely *must* check it out.

And that, my friend, is what learning is all about. e&s

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14–15, 20, 21 — Keiko Satoh; 16, 17, 19 — Lance Hayashida; 17 —Eugene Lubenov and Thanos Siapas

Athanassios (Thanos) Siapas is a professor of computation and neural systems. His work is funded by the Bren Foundation, the McKnight Foundation, the James S. McDonnell Foundation, the Whitehall Foundation, and the National Institutes of Health.

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LEARNING GONE WRONG

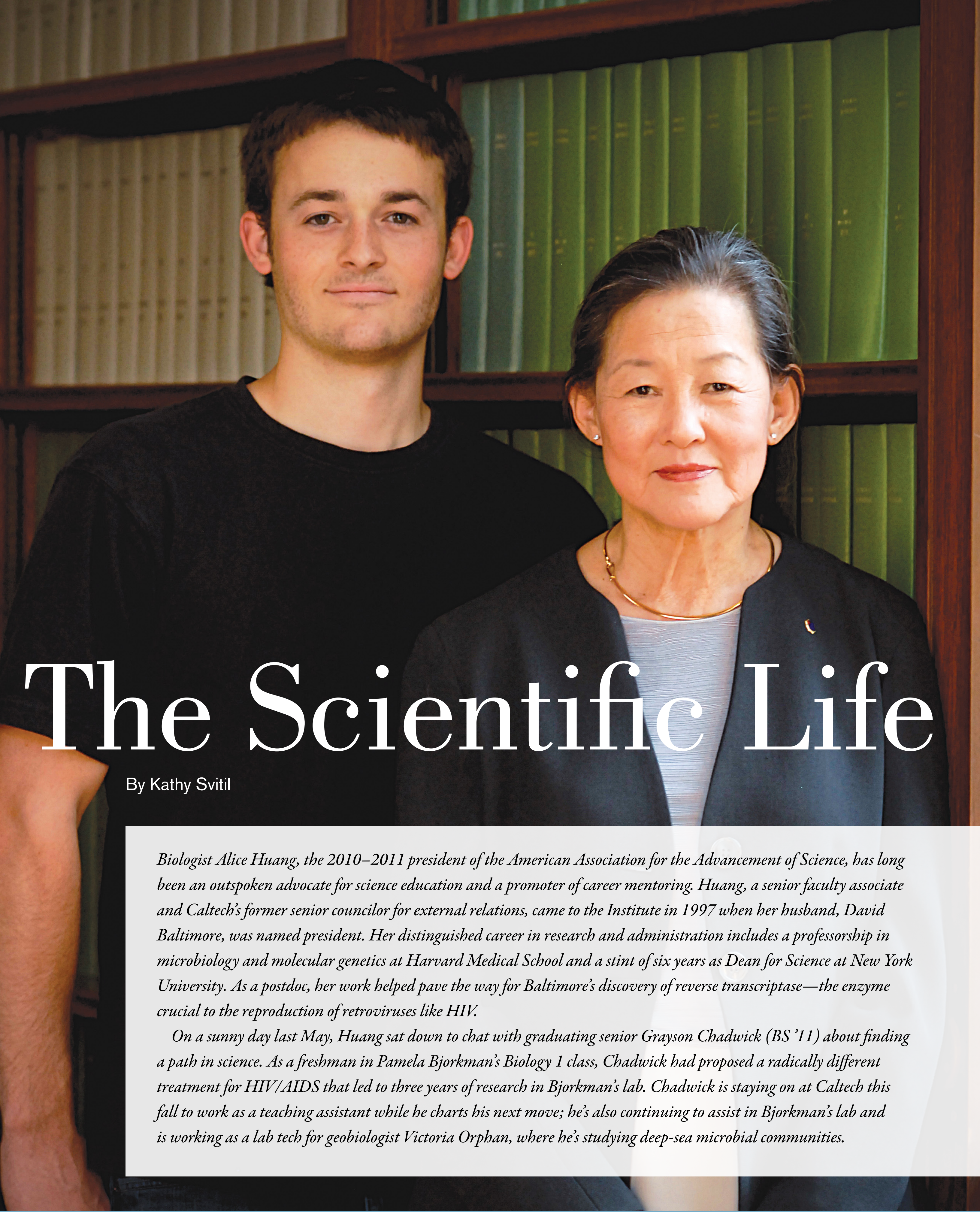
Learning isn't all cupcakes and bike rides. Somewhere amid the synapses and theta waves, things can go awry: memories melt away, habits turn obsessive, positive rewards turn into addictions.

"So often, mental illnesses are derangements of the brain's regulatory behavior, defects in this machinery," notes Mary Kennedy. "If we want better and more specific drugs to treat these illnesses, we really need to understand what is going on at every level."

Thanos Siapas is particularly concerned about vulnerabilities in the ever-so-delicate memory-making circuitry of the hippocampus. "That's a huge part of the impetus to study these systems in such detail," he says. "We want to know exactly how learning and memory work, so that we can build machines that can learn as much as humans, or repair memory problems like Alzheimer's."

O'Doherty, for his part, is focused on how just a little bit of "overexuberance" on the part of a person's habit system could lead to obsessive-compulsive disorder or addiction. O'Doherty notes, "For instance, the habitual learning system could get hijacked by drugs of abuse. If a smoker has a cigarette every time she has a cup of coffee, drinking coffee will become a cue that will signal the response of lighting up a cigarette."

And yet, addiction isn't a given for every single person who picks up a cigarette, nor does every Las Vegas visitor wind up a compulsive gambler. Which is why it's important to tease apart the differences in behavior and brain wiring between folks who become addicted to gambling or nicotine or recreational drugs and those who don't. Says O'Doherty, "We need not only to investigate how learning goes wrong, but to look at the people in which it goes wrong," as he, Professor of Economics and Neuroscience Antonio Rangel (BS '93), and others are beginning to do.



The Scientific Life

By Kathy Svitil

Biologist Alice Huang, the 2010–2011 president of the American Association for the Advancement of Science, has long been an outspoken advocate for science education and a promoter of career mentoring. Huang, a senior faculty associate and Caltech's former senior councilor for external relations, came to the Institute in 1997 when her husband, David Baltimore, was named president. Her distinguished career in research and administration includes a professorship in microbiology and molecular genetics at Harvard Medical School and a stint of six years as Dean for Science at New York University. As a postdoc, her work helped pave the way for Baltimore's discovery of reverse transcriptase—the enzyme crucial to the reproduction of retroviruses like HIV.

On a sunny day last May, Huang sat down to chat with graduating senior Grayson Chadwick (BS '11) about finding a path in science. As a freshman in Pamela Bjorkman's Biology 1 class, Chadwick had proposed a radically different treatment for HIV/AIDS that led to three years of research in Bjorkman's lab. Chadwick is staying on at Caltech this fall to work as a teaching assistant while he charts his next move; he's also continuing to assist in Bjorkman's lab and is working as a lab tech for geobiologist Victoria Orphan, where he's studying deep-sea microbial communities.

E&S: When you were young, Alice, you wanted to be a physician, and you, Gray, started Caltech interested in physics. But you both later switched gears. How did that happen?

Chadwick: For the most part, I feel like everyone here decided they wanted to do science at a pretty young age, but none of us really knew what that meant. Through junior high, I was primarily interested in math, but then I read a book called *Time Travel in Einstein's Universe* and I became a theoretical physicist wannabe. Then I did some internships at the UC Santa Cruz Institute for Particle Physics, and I thought I was really interested in particle physics. But once I got here, and learned more about it, I got a little disillusioned with how theoretical physics and particle physics are done these days, in these giant collaborations, and I was no longer as interested in doing that. I mean, you see papers come out of CERN [the European Organization for Nuclear Research] and the authors' list is longer than the paper itself.

Huang: Changing your interest from physics to biology is not at all surprising. Many students change fields. I started out expecting to go to medical school because I wanted to save lives and heal people; and then I realized that medicine wasn't exactly the best track for me and I turned to research. I never knew before that research can also save lives and help people.

Chadwick: But even after you went to research, your path wasn't so normal.

Huang: Once I figured out that I wanted to be at a research university, I had a fairly representative career in academic science. After I received my PhD, I got myself into the laboratory of a hot young virologist [David Baltimore] at the Salk Institute. There were not that many virologists at the time—I think everybody in the field knew each other. Eventually we married and I followed him to MIT as a research associate. It was so much fun working together, just doing research became my end goal. I realized eventually that as much as I was enjoying being in the lab with my husband, it was a good idea to strike out on my own, and I applied for a job as an assistant professor at Harvard in the medical school.

Over time, I was promoted up the academic ladder and got tenure, which is a big deal. But I wondered, is this something that I'm going to do for the rest of my professional life? That could be 25 years or more. Sometimes, even though you work very hard to get something, once you get it, it's a downer. So when my husband wanted to move to New York City, I thought that might be a good change. I went to the dean and asked him, "What does one do after being a tenured professor at Harvard?" He said, well, there are several natural things. You can just go to another institution and do exactly the same thing—which was not what I wanted to hear—or you can go work for a nonprofit foundation that gives money to support science, *or* you can go into administration in science and help young people succeed.

So I followed David and established my laboratory at NYU, but I also took a job as an administrator part time. I became dean for science. From then on, I became more interested in administration and finally closed my laboratory in 1994. At Caltech, I did administration full time, as senior councilor for external relations, which was a title I made up. What that means is that I coordinate research activities—for example, putting together our faculty working on medically related research with physicians as well as with engineering groups at places like the Jet Propulsion Laboratory.

E&S: Do you find that more satisfying than doing research yourself?

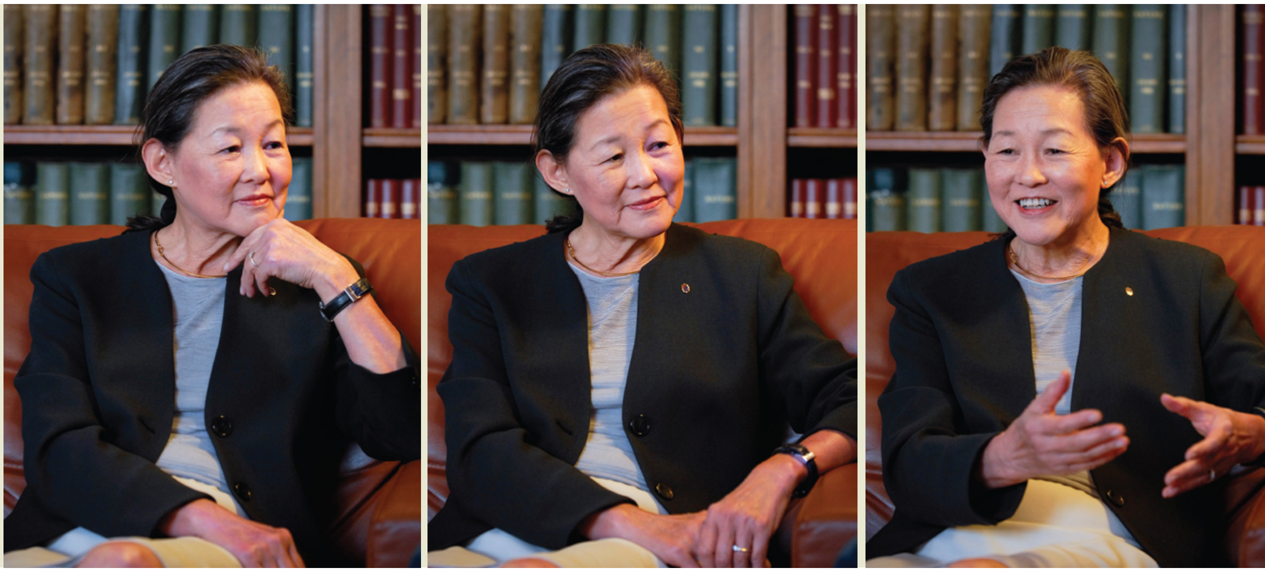
Huang: It's satisfying in a different way. I've helped young professors get recognition and move on in their careers. You get the same sort of feeling as when you're teaching students. It's not making the discovery yourself, but you're opening up the eyes of the students to something that they've never thought about or seen. And I say that's like opening doors for people so that they can walk through them more easily.

E&S: Gray, how did you end up working in Pamela Bjorkman's lab on HIV as just a sophomore?

Chadwick: At the end of Pamela's Bi 1 class, there was an extra-credit assignment to come up with a new idea for treating HIV. Pamela's lab was trying to engineer antibodies that were really good against HIV, which we would give to David's [David Baltimore's] lab and they'd use their gene-delivery vectors to put those genes into people. HIV infects by binding to CD4 and CCR5 receptors on T cells. I wanted to put the genes for those receptors into red blood cells. Red blood cells have no nuclei and there's lots of them, and the idea was that if they expressed the HIV receptors on their surfaces, they'd just sop up the HIV. So the red blood cells would get infected by HIV, but since they don't have nuclei the virus wouldn't be able to replicate inside them.

Huang: So it'd be a dead end for the virus? Have you tried any experiments to see if HIV can get into red blood cells?

Chadwick: I've made red blood cells in the lab, by differentiating them from stem cells, and have infected other sorts of cells with gene-delivery viruses, but as of right now, I'm kind of stuck. It's tricky infecting stem cells and I'm sort



of stumbling through these protocols that I've never really done before. But I think there's nothing really keeping it from working.

Huang: Well, all of the more obvious things for HIV have been tried, so you need to think outside of the box. That's what is fun about research: you can let your imagination sort of take over.

Chadwick: I even have a protocol lined up, but it's pretty time-consuming and the tissue-culture stuff is really scheduled. You do x amount of work every two days, and then two and a half weeks from when you start, you have to be able to spend days doing analysis.

Huang: It really runs your schedule.

Chadwick: Which is one of the reasons why I went over to Victoria's lab. I can go do the work whenever I get a hankering to do some science because the scheduling requirements are a lot looser. But I would love more than anything to get something published on the HIV stuff. I would definitely not be heartbroken if it didn't end up working, but I would love to see something come out of it. I'm really hoping I can get some stuff done on it next year.

Huang: You really just have to design the best experiment you can and see what happens. You can sit around and think of all the reasons why it won't work, but in the end it's really the doing of it.

Chadwick: What I would hate most is to leave this as a burning question that never really got answered. There are times when I feel like I should just give this to some freshman who would be excited about it, but I think it'll be my hobby next year when I'm not doing my other work.

Huang: Also, you're working right at the forefront of the unknown, and that is exciting unto itself. It isn't as if you were repeating work that someone else has done, or making a small variation. You're really trying to do something that is new. Have you been exposed to the neuroscience that goes on at Caltech? Have you taken any of the neuroscience courses?

Chadwick: I took the intro course with Henry Lester, and one on neurological diseases with Paul Patterson. I think diseases are particularly interesting, not so much from a treatment side, but just as really interesting problems.

Huang: Disease tells you about how things function, because it's only when some process is disrupted that you can begin to see where the normal route should have gone. I asked you about neuroscience because when you start out like this, it's nice to talk to different people and find out what they think are the areas in science that are ready to open up and start providing paradigm shifts. When science is at that stage, it's easier to find exciting experiments to do. It's easier to make your own reputation, and it's easier to pick off the low-hanging fruits of a scientific problem. When I got into virology that was exactly what was happening—although I didn't understand it, except in retrospect. Now virology is a ripe science. The questions are still exciting, but they really are several layers down and much harder to get at.

Chadwick: Yeah, absolutely. When I was excited about physics, what I was envisioning was Einstein doing his thing, or Cavendish and his experiment in the basement of his mansion, where he measured the gravitational constant with giant lead balls. That was really cool. Now I feel there's less room for discoveries like that.

That's sort of why I moved a little bit away from the biomedical side of things, because when I look through the literature on HIV or other diseases, every paper is such a little tiny part of some little tiny protein interacting with one other thing. Some of these systems look really interesting but they're so well-studied and, like you said, they're so many layers down that the big picture is kind of lost.

Huang: Exactly.

Chadwick: So I guess that's why I was getting more excited about microbiology, and particularly environmental microbiology in Victoria's lab, because there's such an incredible diversity—there's something like a million bacteria in every milliliter of sea water, and 10 times that many viruses. It's a very different thing because we can't do any genetic modifications of these organisms. In Pamela's lab, we'll clone some genes, we'll put them into the cells, and we'll get this huge list of things we can do to them. In Victoria's lab, we can isolate the microbes by density gradients, and use various techniques to try and answer our questions, but there's a lot of things that we can't do without a pure culture. We don't have a sequenced genome. But the differences between the organisms that are being discovered are just enormous.

Huang: They're certainly very different.

Chadwick: And it's hard to figure out how to even ask questions. We can't do any genetic modifications.

Huang: You can't clone them.

Chadwick: You can't do a lot of stuff, although we did just do some thin-section electron-microscopy images and saw structures inside the cells that are like nothing anyone has ever reported.

Huang: Do you know that you're really caught between two kinds of science? One is more descriptive, without manipulating it too much because you can't. But you are discovering something new and exciting. In the other kind of science, you manipulate and change things, but you can't predict where it's going to lead you.

Chadwick: My fantasy would be to somehow figure out some way to merge them. I need a lot of time to figure out what I'm doing, in other words. I'm very anxious to just do lab work.

Huang: And explore more of what Caltech has to offer you.

Chadwick: Yeah. As a student, I would take lots and lots of classes, although I wouldn't do particularly well. One term I took seven science classes.

Huang: They let you do that?

Chadwick: You have to work your way up to it. And I actually got a B+ in every single one, which is kind of low for some people here. But you have to put in so much work to do any better. And I just wanted to take as many different classes as I could and get a feel for things, and learn where to look for answers. I honestly wouldn't have any trouble hanging on here for two years, if that ended up happening.

Huang: You'll pick up a lot. You certainly have enough to look at and to do.

E&S: How do you think you'll know when you find the right path?

Chadwick: I don't really think there will be a right path—that I'm going to say this is my plan for the next 10 or 20 years. I think I'll just kind of find it somehow. The connections I've made with people have been sort of serendipitous. None of it's been planned. Next year, I don't really know what to expect of TA-ing and being a technician. I'll probably keep sneaking out to work in Pamela's lab on nights and weekends.

Huang: Someone told me, when I was starting out, that the biggest gift that you can get in life is to be doing something that you really enjoy. If you have a passion about it, it's not work. You want to wake up every day and go and do it. And if you are so lucky to find what you really enjoy, then stick with it and do your very best, that usually will lead to the next thing. I think it's really as simple as that. That's what you're looking for, Gray, when you say that you might go back to Pam's lab on nights and weekends. That is something that you *want* to do. You should follow your nose.

PICTURE CREDITS:
Bill Youngblood

LESSONS FROM JAPAN

By Katie Neith

Tectonic plates worldwide have been slipping, sliding, and shoving one another around like sumo wrestlers for eons untold. But the titans have been hitting the mat recently, starting with the magnitude 9.1 Sumatra-Andaman earthquake in December 2004, which was followed by the 8.8 Maule shaker in Chile in February 2010. The latest in this string of large earthquakes, of course, is the March 11 Tohoku event, registering at a magnitude of 9.0.

When the bouts shift to land versus infrastructure, the human race is always on the losing end. Death tolls from Japan's earthquake and the resulting tsunami are estimated to exceed 18,000 people. It will take hundreds of billions of dollars to rebuild the country, and cleanup of the heavily damaged Fukushima nuclear plant could take decades. But while the costs are unprecedented, the magnitude of these quakes is nothing new.

"It's not that recent earthquakes are any worse, it's just that our exposure is much greater," explains Mark Simons, a geophysicist at Caltech's Seismological Laboratory. He points to a series of large earthquakes that happened in the late '50s and early '60s and included the biggest one on record—Chile's 9.5-magnitude Valdivia quake in 1960.

"In the 50 years since the Chile earthquake, cities have grown tremendously, which makes the need to understand the specifics of the earthquake processes all the more important," he says.

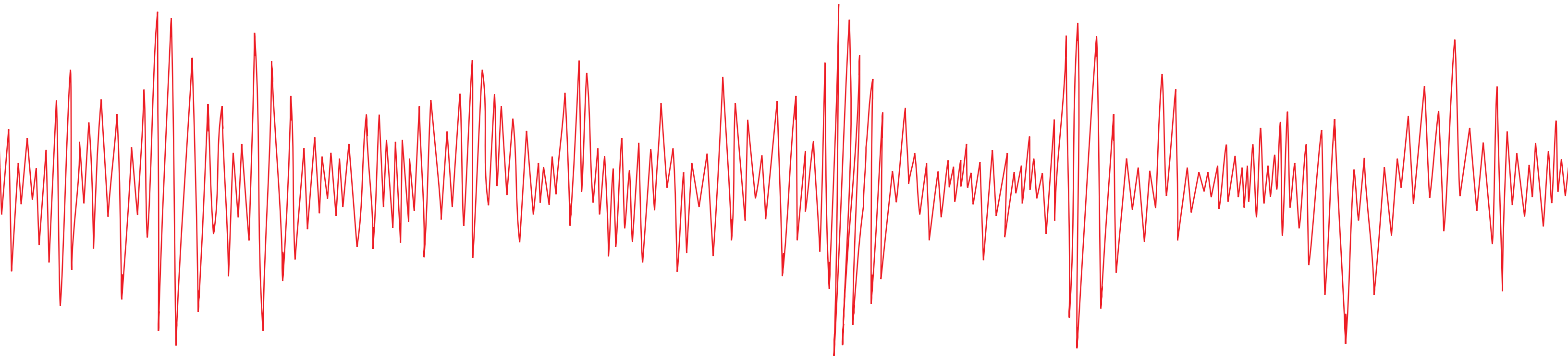
The Tohoku earthquake devastated the land and its people. But rising from the rubble like a phoenix (or *fushicho* in Japanese) is a slew of seismological data that will ultimately help save lives.

"This event is the best-recorded great earthquake ever," says Simons, the lead author of a recent paper in *Science* that presented the first large dataset from the temblor. Published online in May and in print in the June 17 issue, the study was written by 14 researchers from Caltech and JPL, and one from the University of Michigan.

The lion's share of the recordings used in the study came from GeoNet, a dense network of more than 1,200 GPS receivers that measure local ground displacements. Japan was the first nation to embrace GPS technology for nationwide tectonic monitoring, and the Geographical Survey Institute of Japan installed the GeoNet array some 15 years ago—an investment that has paid huge dividends. The paper also drew on arrays of broadband seismometers from around the world, as well as open-ocean tsunami data from buoys, to put together a detailed picture of how the earth moved that day.

THE STRESS OF PREDICTING STRAIN

The earthquake's punch came from a surprisingly compact region, says Simons. A megathrust quake such as this one occurs when one tectonic plate is being jammed underneath its neighbor in a region called a subduction zone—in this case, where the Pacific Plate dips below Japan. Since the energy released during a quake is proportional to the area of the fault that moves,

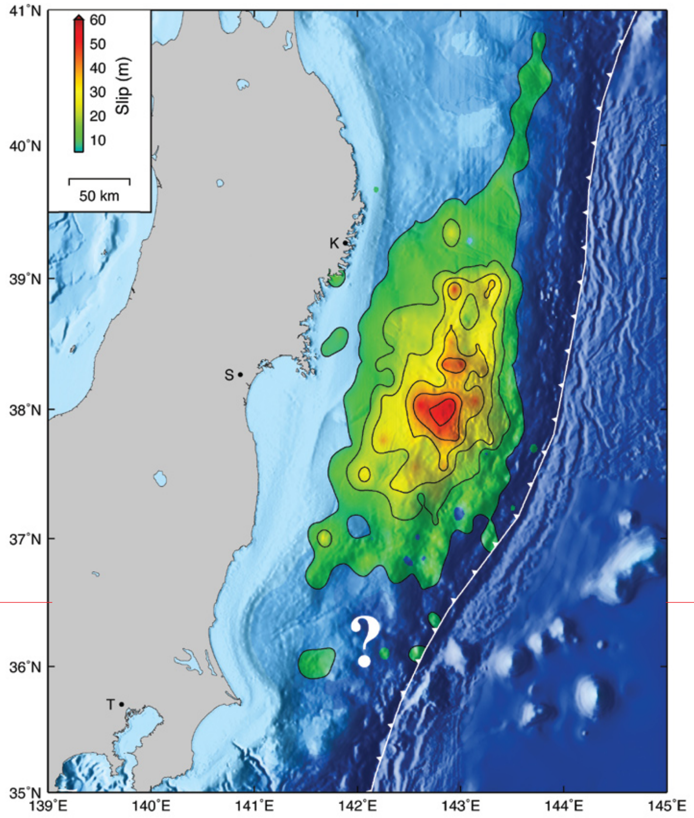


scientists expected to see a rupture zone of at least 500 kilometers. Instead, the significant slip was confined to a region about half that length—some 250 kilometers, or roughly the distance between Los Angeles and Bakersfield.

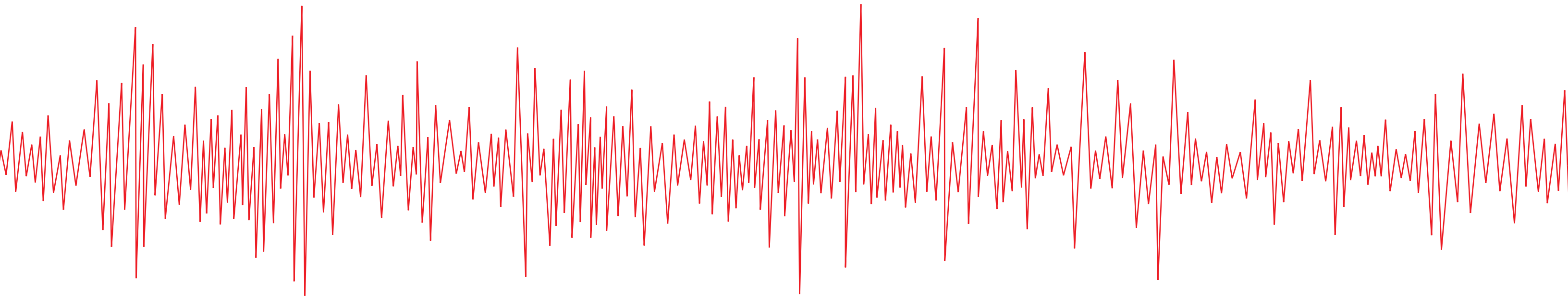
Furthermore, the area where the fault slipped the most—40 meters or more—lay within a 50- to 100-kilometer-long segment. “This is not something we have documented before,” says Simons. “I’m sure it has happened, but only in the past 10 to 15 years has technology advanced to the point where we can estimate localized slips accurately.”

The devastating tsunami occurred because the high-slip zone extended up the fault plane almost to the seafloor, as geologist Jean-Philippe Avouac, director of Caltech’s Tectonics Observatory, pointed out in an online Nature commentary June 15. “The large quantity of slip at shallow depth came as a real surprise to me,” says Avouac. Conventional wisdom holds that megathrust earthquakes originate at great depths, usually 30 to 40 kilometers underground, where the crushing mass of rock above keeps the plates firmly pinned together. But Tohoku’s hypocenter—the point within the earth where the shaker started—was only about 24 kilometers down. “The common belief is that the topmost 10 kilometers of a subduction zone is buttered with clays that promote aseismic sliding, or gentle moving of the plates that doesn’t produce seismic slip,” he says. The lesson here, says Avouac, is that we need to rethink how we model the way that plates lock into place along different areas of the fault. Current methods tend to assume minimal locking near the surface if the available geodetic data is sparse, as was the case here. The fault rupture began approximately 100 kilometers offshore, far from GeoNet’s coverage area.

The amount of slip also surprised seismologist Hiroo Kanamori, who was in Japan at the time of the quake and has been studying the region for many years. It was believed that the relatively soft material of the seafloor could not hold much stress before giving way. Because the zone of maximum displacement was so small, “the local strain was nearly five to 10 times greater than we normally see in large megathrust earthquakes,” he notes.



The fault responsible for the Tohoku quake starts at the Japan Trench, as indicated by the barbed line, and dips under Japan. In this model of the event, estimated fault slip is shown by colors and by eight-meter contour intervals. The earthquake potential to the south (the question mark) remains unknown.



"It has been generally thought that rocks near a trench could not accommodate such a large elastic strain." (Incidentally, "stress" and "strain" are not the same: if you are hoisting a barrel of bricks with a winch and pulley, the stress is the degree of tension on the rope and the strain is the amount that the rope stretches.)

The researchers are still unsure how so much strain accumulated. One possibility is that the subducting seafloor has something unusual on it—an underwater mountain range, perhaps—that caused the plates to get stuck.

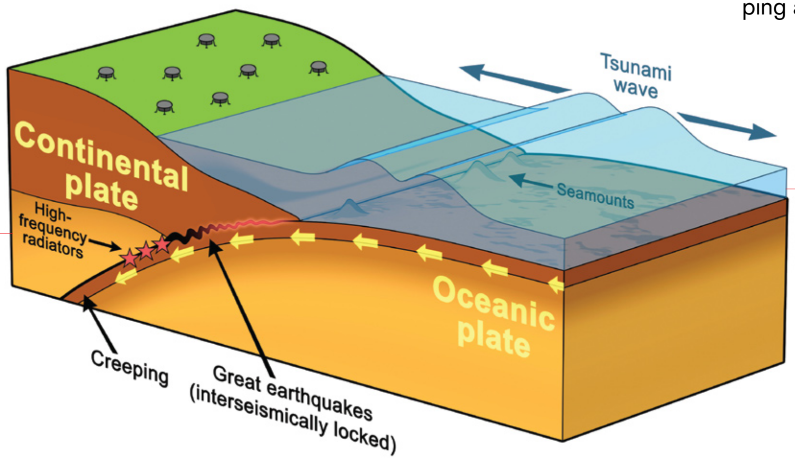
"Whatever the cause, the Pacific Plate and the Okhotsk Plate had been pinned together for a long time, probably 500 to 1,000 years, and finally failed in this magnitude 9.0 event," says Kanamori. "Hopefully, detailed geophysical studies of seafloor structures will eventually clarify the mechanism of local strengthening in this area."

Avouac advocates paying closer attention to anelastic deformation, also known as creep. Elastic strain stores up stress that is released in large earthquakes, while anelastic strain dissipates stress and lowers the potential for strong shakers. Measuring anelastic strain "is a hard problem, but it is high time to try to address it," he says. "It affects the rate at which elastic strain builds up, and therefore our estimates of the probability of large earthquakes."

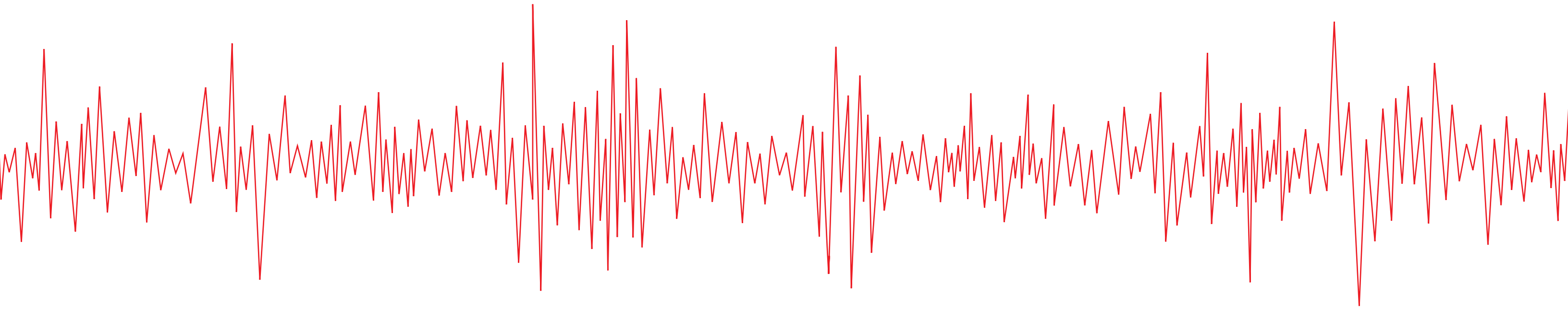
The conventional wisdom was shaken yet again when seismologist Jean Paul Ampuero, who studies earthquake dynamics, noticed that the high- and low-frequency seismic waves came from different areas of the fault. "The high-frequency seismic waves in the Tohoku earthquake were generated much closer to the coast, away from the area of the slip where we saw low-frequency waves," he says.

It turns out that the largest load on the plates, which is what generates the highest-frequency waves, occurred at the *edges* of the slip—not near the center, where the fault began to break. Simons compares it to ripping a piece of paper in half. "The highest amounts of stress aren't found where the paper has just ripped, but rather right where the paper has not yet been torn," he explains. "We had previously thought high-frequency energy was an indicator of fault slippage, but the two don't correlate in our models of this event." How the fault reacts to the stress is equally important; it appears that only the deeper segments produced the high-frequency energy.

Ampuero's findings highlight the need to look more closely at the mechanical properties of faults, he says, and to integrate that information into risk-assessment models. The waves that do the most damage to a building are the ones at its resonant frequency. The building wants to shake at that frequency, and resonant waves pump energy into the building like a grownup pushing a kid on a swing set. These resonant waves are the "high-frequency" ones described above, although the average person wouldn't think of them as such. The lowest frequencies audible to the human ear begin around 15 hertz, while a 100-story skyscraper responds to waves of around 0.1 hertz. Moving up the scale, 1-hertz waves are tuned to 10-story midrise buildings, and 10-hertz waves are the source of bad vibes for single-story structures. Predicting how those waves travel



In this diagram, the rippling line between the continental and oceanic plates represents the area that slipped in the earthquake. The high-frequency waves radiated from regions at the deepest edge of the slip zone, closest to the shore. The gray circles represent the locations of GPS instruments.



will help scientists quantify earthquake hazards.

"We learn from each significant earthquake, especially if it is large and recorded by many sensors," says Ampuero. "The Tohoku earthquake was recorded by upwards of 10 times more sensors at near-fault distances than any previous one. This will provide a sharper, more robust view of earthquake rupture processes and their effects."

PREDICTING THE UNPREDICTABLE

"We learned a certain amount of humility with this earthquake," says Simons. "The mistake we made was that we did not adequately describe what we don't know."

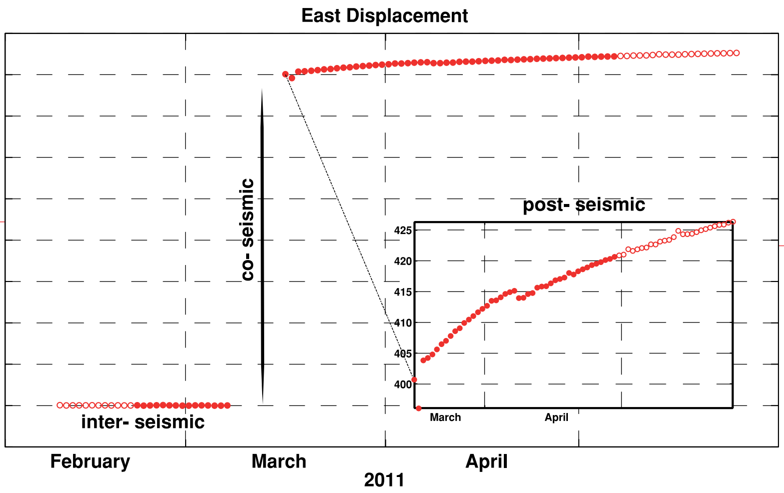
In fact, very little was known about the area, due to its historical quiescence. However, many seismologists assumed that a large megathrust event was unlikely to occur there. For example, Kanamori and others had theorized that where a plate is very young, it tends to produce big earthquakes. The quake in Chile last year happened on a plate that is 10 million years old—a baby in geologic terms.

"Where old plates are subducting, we don't normally have giant earthquakes," says Kanamori. "This explanation usually works. However, the plate off the coast of Tohoku where this earthquake occurred is old, about 130 million years. This event was exceptional because it revealed an unusually strong coupling near the Japan Trench that we did not know about."

Simons points out that many models of the area existed, all of which predict relatively frequent earthquakes of magnitude seven or eight. The *Science* paper presented a new model, consistent with the buildup of more than a thousand years' worth of elastic strain, that was capable of producing a magnitude nine. "I think that it behooves us to spend much more time thinking about describing the family of allowable models, as we are here at Caltech, and not just focusing on single models," he says.

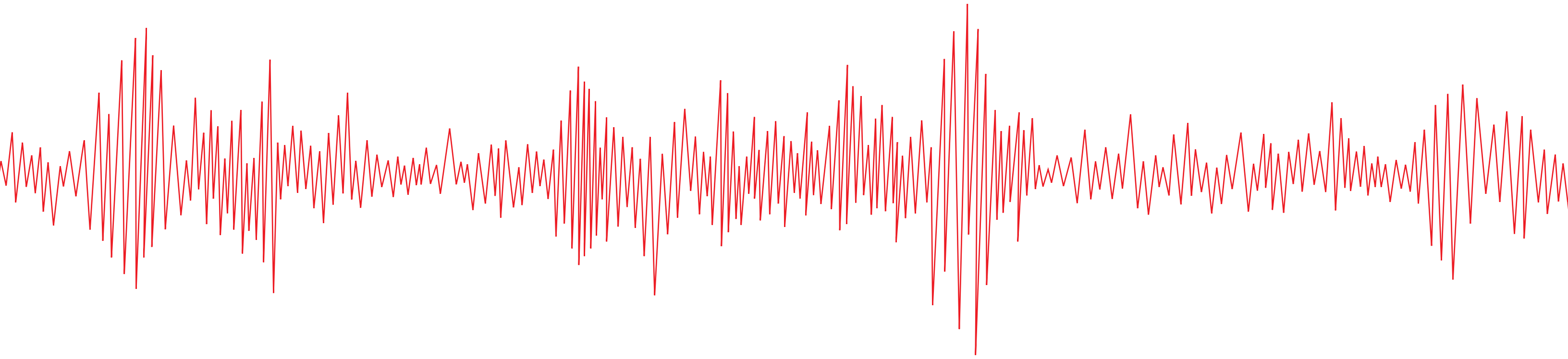
Combining innumerable bits of information from different technologies and various sources has taught the researchers the power in not being too provincial. "What was key with our *Science* paper is that it involved the geodesists and the seismologists, all trying to come together with one coherent picture that made sense," says Simons. "For us, that is the joy of being in the Seismo Lab. It was a great opportunity to put our minds together. Of course, our picture will no doubt evolve over the next year, as more data become available and as our models get refined."

Pooling their resources enabled the Caltech/JPL team to post some preliminary findings online within weeks of the quake, and the time between the event and the *Science* paper was only two months. But the most critical information went public almost immediately. The team posted the earth-movement vectors as they were calculated from the GeoNet data, and within a week they had been downloaded a couple thousand times. "This is a highly specialized product, not a YouTube video," says Simons. "And yet, there is clearly an audience for this kind of information, and a need to disseminate it rapidly, so that response agencies and other scientists can act on it."



This plot from a GPS receiver in northern Japan tracks the station's daily positional changes along an east-west axis in the month before and the two and a half months after the March 11 earthquake. Having this kind of data covering all the phases of the seismic cycle is critical for developing detailed mechanical models of fault systems.

The data was processed by ARIA, a Caltech/JPL collaboration, and rendered by grad student Francisco Ortega (MS '08).



AN UNCERTAIN FUTURE

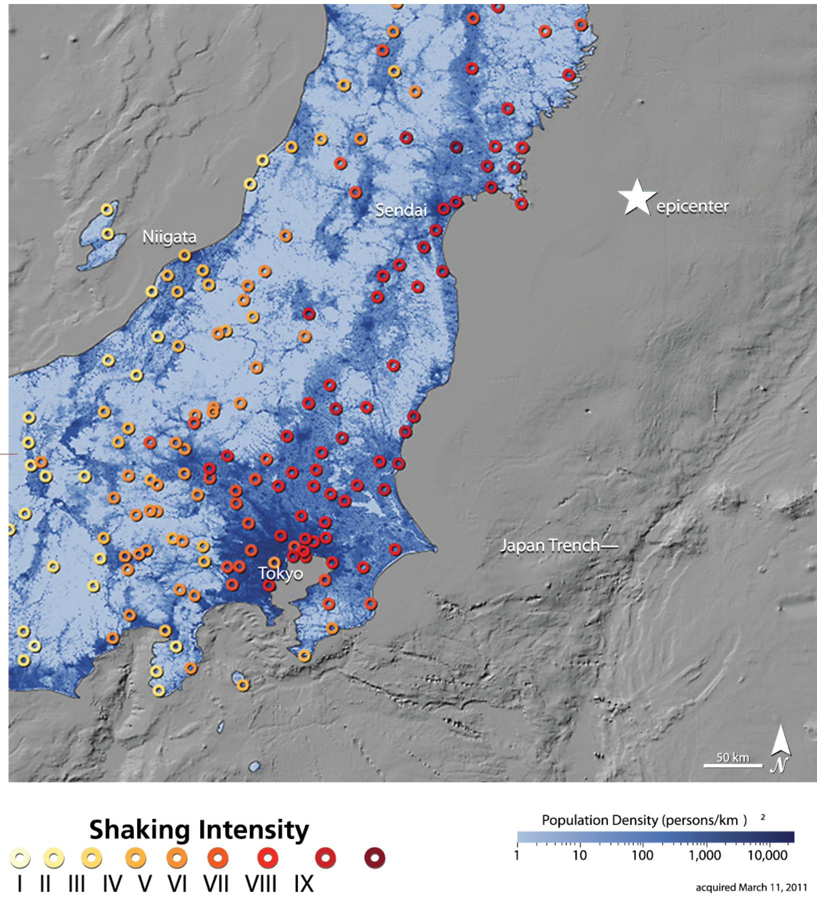
The data crunching continues, as does the assessment of how different technologies worked (or didn't) to produce reliable information. The lessons learned will help usher in a new era in earthquake science.

"We have long relied purely on seismology to respond to earthquakes on a very short timescale," says Simons. "Now we are entering the age of GPS and other remote-sensing techniques." Space-based geodesy, which includes GPS and satellite radar techniques, can measure subtle deformations in the earth's surface over thousands of square kilometers.

Simons points to two Caltech-led projects that are pushing the boundaries on how we could potentially gather data about disasters and get that information out fast to fire fighters, FEMA field agents, and other people who need it. One is a collaboration with JPL called the Advanced Rapid Imaging and Analysis (ARIA) project, which is currently in the prototype-development phase. "The goal is to make space geodesy more relevant to rapid response by producing processed, useful data within hours of an event, as well as to produce physically based models constrained by the data," he says. "The current focus is earthquakes, but we expect to extend the capability to volcanoes, floods, fires, and other natural disasters."

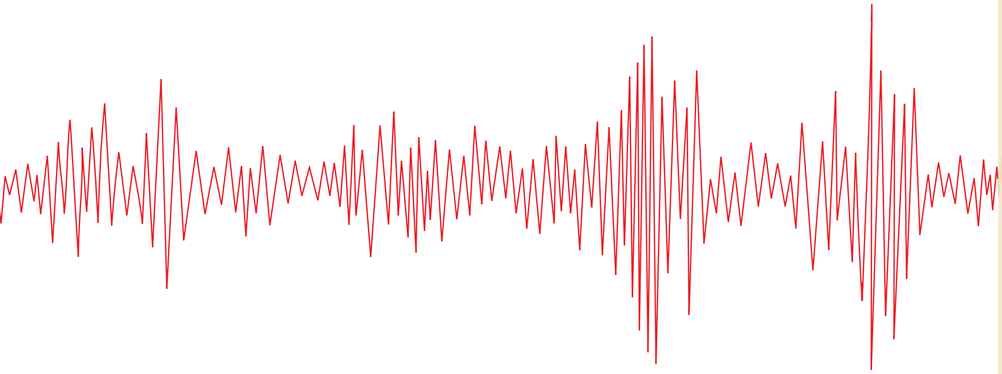
The other is a concerted effort to drum up support for a NASA satellite designed specifically for interferometric synthetic aperture radar, or InSAR. InSAR compiles radar swaths taken in successive orbital passes to map surface deformation, such as fault creep, in three dimensions over time. "InSAR is an important part of ARIA," says Simons, "as is GPS and seismology. But the current handful of InSAR-capable satellites from which one can get serendipitous data are European or Canadian." (The Japanese satellite that imaged the Tohoku event was shut down just a few weeks later after an onboard power failure.)

"We see time and time again that the rapid dissemination of information is important, yet we're going in the wrong direction in terms of getting into space the assets that would enable dissemination," says Simons, who notes



Left: The colored circles on this map represent shaking intensities compiled from USGS data. IX is "violent"—heavy damage, up to total collapse of some buildings. Note the number of VIIs and VIIIs near Tokyo, well away from the epicenter (red star). The blue hues are population-density data from the Oak Ridge National Laboratory.

Right: A solar-powered GPS station outside the town of Putre in northern Chile, near the Bolivian/Peruvian border, installed by Caltech geophysicists to monitor earthquake-cycle related deformation. The dome on the rock houses the GPS antenna; its tripod is mounted deeply and permanently into the ground.



that current federal budget proposals include a cut in funding for such advanced technologies.

Kanamori agrees that getting the data out quickly after a big event is vital for hazard mitigation. He says that information needs to be collected on a global scale, since local systems often fail during a natural disaster nearby. This requires good coordination between agencies in different countries so that "in the case of an emergency, they can exchange information and take immediate action," he says.

But while seismology's rapid advances in data collection and analysis may improve the way we deal with emergencies, "natural events do not repeat in exactly the same way, so we do not have the benefit of reproducible experiments," Kanamori says. "We have to deal with often-unpredictable nature, so using rapid, reliable information to prepare for the unexpected is very important."

Mark Simons is a professor of geophysics; Jean-Philippe Avouac is a professor of geology; Hiroo Kanamori is the Smits Professor of Geophysics, Emeritus; and Jean-Paul Ampuero is an assistant professor of seismology.

The research featured in the* Science *paper was funded by the Moore Foundation, the National Science Foundation, the Southern California Earthquake Center, and NASA's internal Research and Technology Development program.

DATA HITS HOME

Ever wonder how much your house might *really* be rocking and rolling during an earthquake? If you're in the Pasadena area, you may have the opportunity to find out. A new project out of Caltech's Seismo Lab is collecting data by installing small seismometers in local homes to create block-by-block "shake maps." The data collected by the Community Seismic Network (CSN) will be used to direct fire trucks and ambulances to the hardest-hit areas shortly after an earthquake.

Because of local differences in the geology that underlies Los Angeles, it's very likely that one block could sustain more devastation than the next depending on how the land responds to the energy of the quake. The CSN deployment is intended to demonstrate how these high-resolution shake maps can be used as a proxy for damage, and the project is slated to last several years.

"Major earthquakes such the March event in Japan increase the public awareness of the hazards of earthquakes and point out the need to provide emergency responders with a map of damage in the minutes to hours following an earthquake," says geophysicist Robert W. Clayton, who is principal investigator on the CSN grant from the Gordon and Betty Moore Foundation that is funding the placement of 1,000 or so sensors in quaint bungalows, stately mansions, and towering office buildings across the greater Pasadena area. "A dense set of measurements of the ground shaking can also be very useful in planning how to rebuild."

Participants will be able to see the information they are contributing to the network. "You can tap the sensor and see how the 'pick' that is generated shows up on the CSN webpage," explains Clayton.

Visit www.communityseismicnetwork.org to volunteer your home or office as a seismometer location. For more information about additional CSN projects, check out "E/Q Phone Home" in the Spring/Summer 2011 issue of *E&S*. *—KN*

PICTURE CREDITS:
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Plenty of Room at

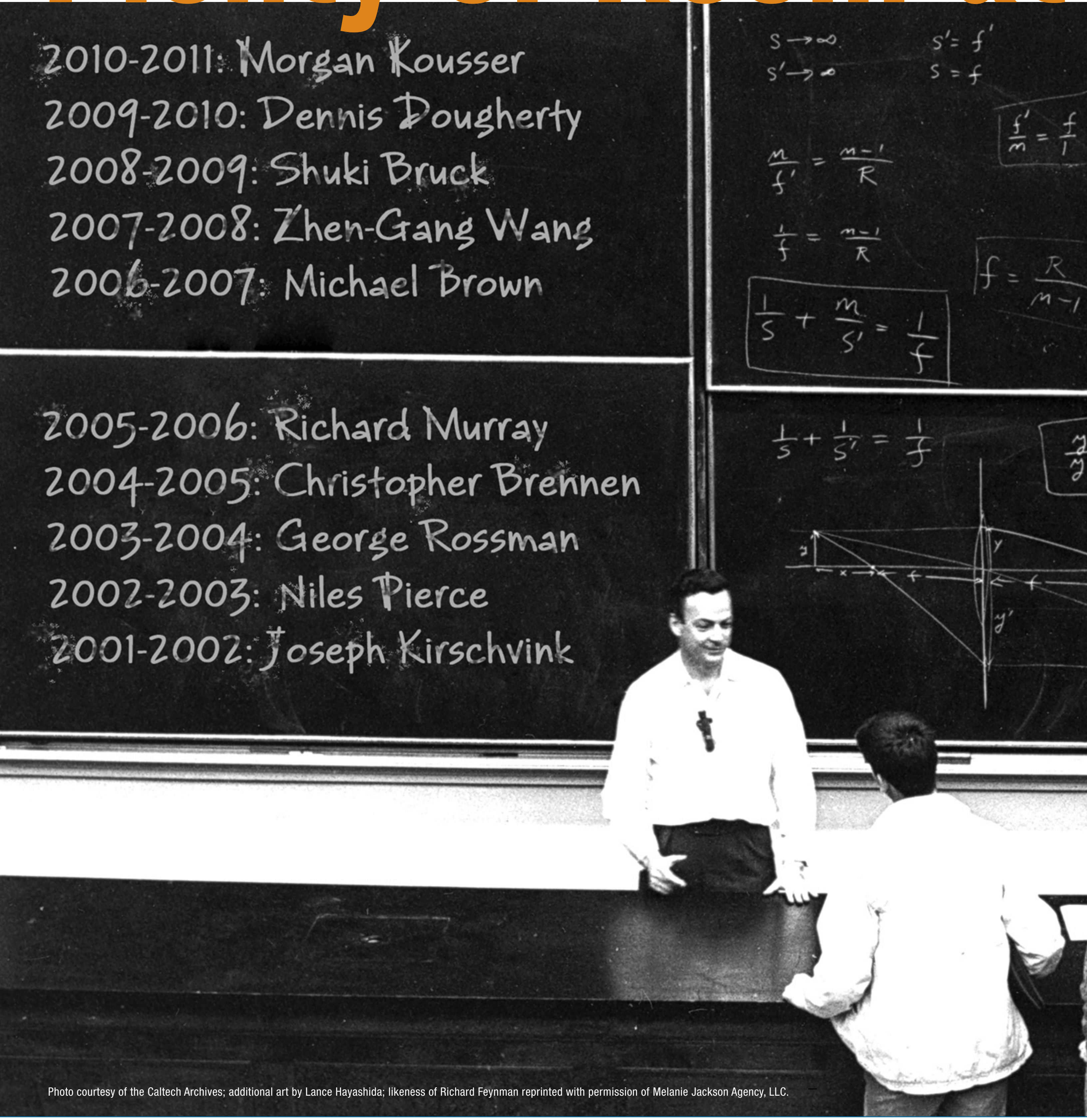
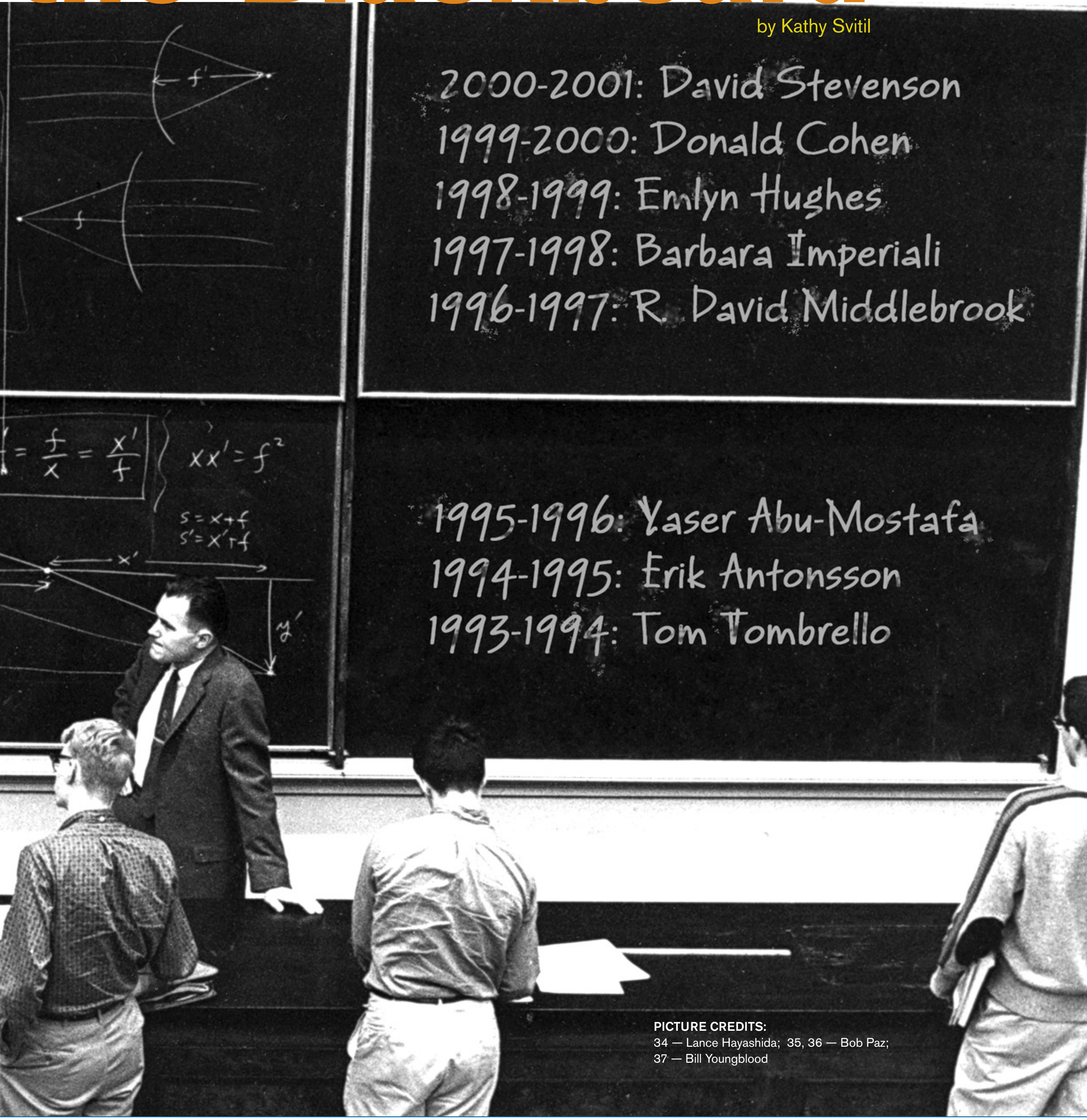


Photo courtesy of the Caltech Archives; additional art by Lance Hayashida; likeness of Richard Feynman reprinted with permission of Melanie Jackson Agency, LLC.

the Blackboard

by Kathy Svitil



2000-2001: David Stevenson
1999-2000: Donald Cohen
1998-1999: Emlyn Hughes
1997-1998: Barbara Imperiali
1996-1997: R. David Middlebrook

1995-1996: Yaser Abu-Mostafa
1994-1995: Erik Antonsson
1993-1994: Tom Tombrello

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37 — Bill Youngblood

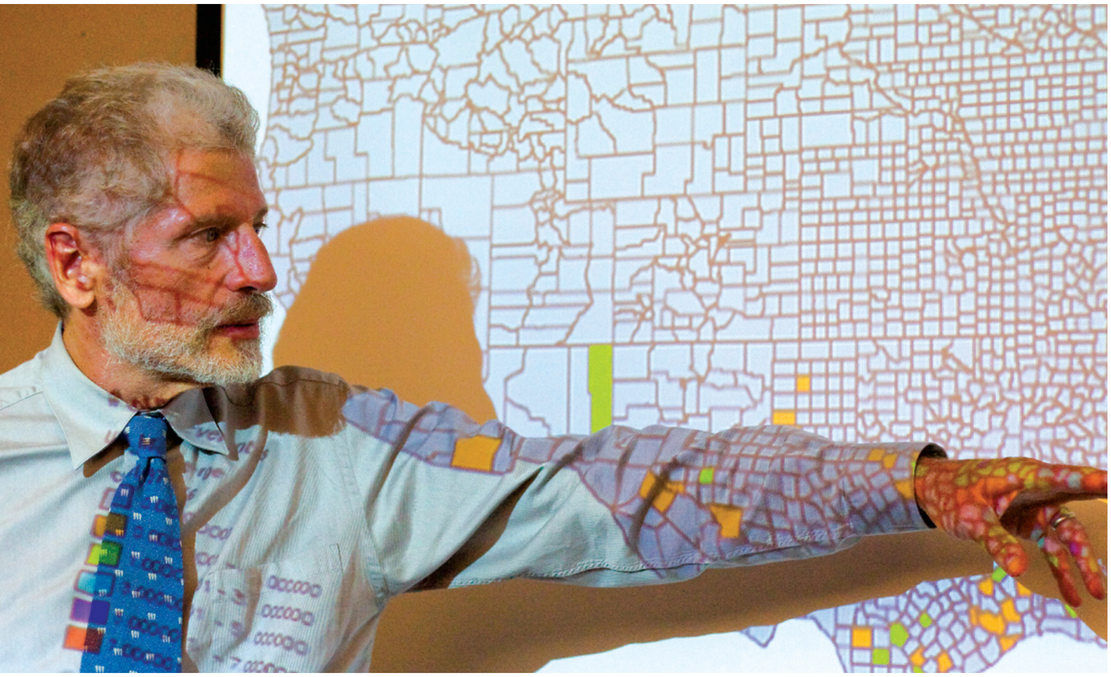
Science alone of all the subjects contains within itself the lesson of the danger of belief in the infallibility of the greatest teachers in the preceding generation.

– Richard P. Feynman, in *The Pleasure of Finding Things Out: The Best Short Works of Richard Feynman*, edited by Jeffrey Robbins (1999)

Caltech is known to the world for its research, but to the student, there's nothing so inspiring as a great *teacher*—one who excites and challenges; one who enlivens the mundane and elucidates the impenetrable with unexpected creativity, patient guidance, and boundless enthusiasm.

Students and faculty nominate Caltech's best for the annual Richard P. Feynman Prize for Excellence in Teaching, established in 1993 and named after the legendary physics professor, Nobel Prize winner, and gifted educator—who recognized that teaching can be as enlightening to the instructor as to the students. "I *don't* believe I can really do without teaching," wrote Feynman in his book *Surely You're Joking, Mr. Feynman!* "When I don't have any ideas and I'm not getting anywhere I can say to myself, 'At least I'm living; at least I'm *doing* something; I am making some contribution' . . . The students keep life going, and I would *never* accept any position in which somebody has invented a happy situation for me where I don't have to teach. Never."

The 18 Feynman Prize winners would likely agree.



Morgan Kousser

MORGAN KOUSSER

A professor of history and social science, Kousser was lauded by Elizabeth Mak (BS '11) for "his ability to make the complex and convoluted subject of constitutional law clear and comprehensible to students more inclined to equations than court opinions."

DENNIS DOUGHERTY

Hoag Professor of Chemistry

His energetic lectures possessed superb organization and exceptional clarity . . . They flowed elegantly without flaw, as he guided the class, always finding exactly the right words for his explanations that always seemed to go a step farther, deeper and beyond the normal lecture.
—Andrey Poletayev (BS '11)

SHUKI BRUCK

Bruck, the Moore Professor of Computation and Neural Systems and Electrical Engineering, was nominated by his IST 4 (Information and Logic) students for the inaugural term of the class, which covers the evolution of information systems. “Shuki’s lectures do an excellent job in engaging the attention of a class-full of students,” wrote teaching assistant Yuval Cassuto (PhD ’08). “With a teaching style that includes impeccably prepared lectures, detailed and informative slides, and more than a bit of entertainment, Shuki skillfully sets a very inviting stage for the students to grasp the deep concepts of the class.”

Zhen-Gang Wang

ZHEN-GANG WANG

Wang, a professor of chemical engineering, was selected for “his mastery of thermodynamics and polymer physics, clarity of presentation, and ability to empower students through the knowledge and experience they gain from his teaching.” Students have described his lectures—conducted without notes—as “amazing” and “incredibly clear,” and Wang as having an “uncanny ability to cut to the heart of a question and provide an answer based on fundamentals.”

MICHAEL BROWN

Brown—the Rosenberg Professor and professor of planetary astronomy—was singled out for Ge 1 (Earth and Environment), and for Ge/Ay 133. The latter, a graduate course on the formation and evolution of planetary systems, always appeared to be “subtly directed by the students,” wrote Colette Salyk (PhD ’09). “The questions, when not immediately answerable, gave the class a feeling that they were involved in helping to solve a mystery.” Although seemingly spontaneous, Brown’s lectures “must have been well thought-out and, perhaps, rehearsed,” she noted. “I liked to imagine him like Feynman, parading around an empty classroom.”

RICHARD MURRAY (BS ’85)

Everhart Professor of Control and Dynamical Systems and Bioengineering

Most Feynman Prize winners knew the enigmatic bongo player only as a colleague, but Richard Murray first met him as a freshman on the opening day of frosh camp. As Murray recalled, Feynman “sat down next to me and started talking about some shells he had found while he was swimming. That willingness to talk to a student typified his approach to teaching.” More than two decades after that encounter, Murray received the Feynman Prize for the same willingness to engage his students and his “enthusiasm, responsiveness, and innovation.”

Chris Brennen

CHRISTOPHER BRENNEN

Hayman Professor of Mechanical Engineering, Emeritus

The use of the word “classroom” as a metaphor for “teaching” is a bit of a misnomer, as Prof. Brennen’s teaching often takes place in unusual places. My first lessons from Prof. Brennen took place in the middle of nowhere in the Mojave Desert, where we hiked for several miles up the crest of a sand dune and slid down on our behinds to cause the dunes to boom. Prof. Brennen’s enthusiasm, even in hundred-degree-plus temperatures, was an inspiration.
—Kathy Brantley (BS ’03, MS ’05)

GEORGE ROSSMAN (PhD ’71)

McMillan Professor of Mineralogy

“George had a way of making everything in mineralogy fun and interesting,” said one former student of Rossman’s introductory mineralogy course (Ge 114). Rossman, the student noted, often brought unusual minerals to class, including a specimen that formed a dipole when squeezed in one direction. “He had one student tie an end with string and put it in liquid nitrogen, being sure not to bang it into the sides of the dewar. Of course the cold squeezed the mineral and it created a dipole and was instantly attracted to the metal sides and just kept banging into one side or another." Another Ge 114 student said "George taught me much more than mineralogy. He taught me how to ask deep questions."

NILES PIERCE

Now a full professor of applied and computational mathematics and bioengineering, Pierce is the only assistant professor to have been awarded the Teaching Prize, for ACM 95/100—a combined graduate- and undergraduate-level applied mathematics course. His award citation noted that Pierce "teaches without oversimplifying and without intimidating, making the material accessible to this diverse group of students" and "possesses an uncanny ability to anticipate the frustrations and challenges of the students."

JOSEPH KIRSCHVINK (BS, MS '75)

Van Wingen Professor of Geobiology

Joe doesn't just think outside of the box; the box is irrelevant. Nothing hinders Joe's ambitions to do new and exciting science. Ideas that require unprecedented experimental setups don't phase him a bit; whatever is needed will get designed, built, tested, and utilized. Students learn from example that nearly anything is possible, and that you cannot let conventional barriers hinder the creative scientific process.

—John Holt (PhD '97)

DAVID STEVENSON

Van Osdol Professor of Planetary Science

Stevenson, who chaired the faculty committee responsible for implementing the revised core curriculum in the mid 1990s, turned Geology 1—the general ed course on Earth and the environment—into a class unlike any other of its kind. "Dave's achievement in conceiving and implementing this course is truly unprecedented," wrote Ed Stolper—then chair of the Division of Geology and Planetary Sciences and now provost—in nominating Stevenson for the prize, "and the tangible benefit is quite remarkable." The three-quarters of the undergraduate population who are not Earth scientists leave the Institute with a deeper understanding of our planet and how we learn about it, he noted, "prepared to address . . . important issues that society will be grappling with (such as global warming) over their lifetimes."

Niles Pierce

DONALD COHEN

Powell Professor of Applied Mathematics, Emeritus

His eloquence in presentation is such that even when he is teaching a very difficult concept, he is able to lead the entire class through the muck of algebra or notation and reveal the essentials of the idea he is presenting, which leads to maximal understanding in his audience. He doesn't dress up simple ideas with fancy language, as many math professors love to do. Nor, however, does he oversimplify and present things as less complicated than they really are.

—Mike Fisher (BS '99)

EMLYN HUGHES

Then associate professor of physics, now a visiting associate in physics

"Over and above being a good lecturer," said Ken Libbrecht (BS '80), the executive officer for physics, mathematics and astronomy, in nominating Hughes for his core quantum mechanics class, "Professor Hughes obviously applies a great deal of creativity to his teaching. He jumps around, throws things, has an evil twin brother, and spends time in nearly every lecture telling insightful stories about physics, and about life in general." Hughes's efforts to make quantum mechanics accessible don't go unappreciated by students, who describe him as "charismatic," "entertaining," and "rad" in course evaluations. "Emlyn," one student concluded, "should be canonized."

BARBARA IMPERIALI

Then a professor of chemistry, Imperiali—who, during her Caltech tenure, was described by her students as "dynamic and intense" with "infectious" enthusiasm—was singled out for the Feynman Prize as a "lively lecturer" (of both introductory and upper-level chemistry courses) and an "inspirational mentor" to her research students.

R. DAVID MIDDLEBROOK

Dozens of former students—including working engineers, university professors, and company presidents—wrote glowing letters supporting the nomination of their mentor. For more than 40 years, the beloved electrical engineering professor, who passed away in 2010, "did not only teach analog circuit design," said one, "but a far more important concept: he taught us *how to think*! . . . he taught us how to concentrate immediately on the essentials of a problem and disregard the 'non-essentials' (only to add them in the final stages of the problem). But when you 'think' about it, isn't it the way we should tackle large research problems? Isn't this the way we should even handle family life matters? Basically, concentrate on the essentials and do not get fooled with the peripherals!!"

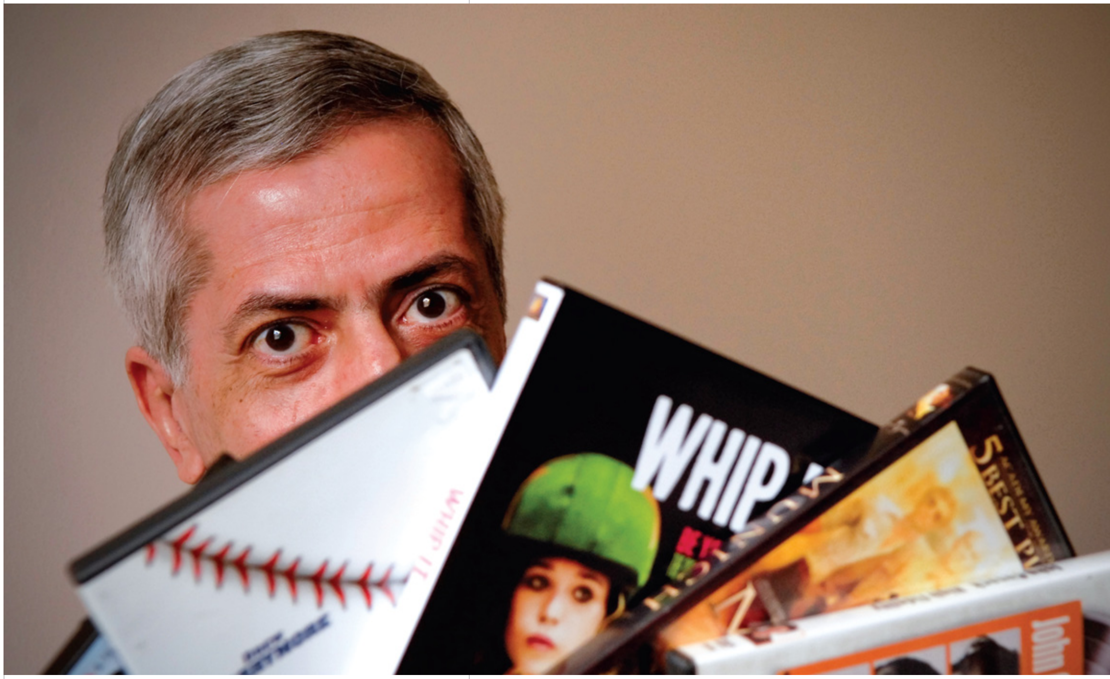
YASER ABU-MOSTAFA (PhD '83)

Professor of electrical engineering and computer science

Abu-Mostafa, the selection committee noted, "has consistently demonstrated that no-frills teaching is not a lost art. Year after year, using only chalk and voice as media, he has tamed Caltech's challenging curriculum for a very grateful group of students. He takes a multi-faceted approach to every topic, often fooling his students into mastering even the most difficult material."

ERIK ANTONSSON

Then associate professor of mechanical engineering, now a visiting associate in mechanical and civil engineering, Antonsson created ME 72, Caltech's Engineering Design Laboratory, with a simple purpose: to help students learn about the "design of new *things*, and the solution of open-ended, ill-defined problems." The result was "wonderful," wrote Tom Tombrello in supporting Antonsson's nomination for the Feynman Prize. "The students work very, very hard; they do not complain; they have a good time; and they learn a tremendous amount. This is truly the essence of extraordinary teaching skill. Dick Feynman never took the ordinary or expected path in solving a problem, and that gave us wonderful new ways of looking at the world. Erik has taught in an unusual way and done what we all strive to do—except the result is better than most of us manage."



Yaser Abu-Mostafa

TOM TOMBRELLO

Kenan Professor and professor of physics

The Feynman Prize selection committee noted two innovative undergraduate courses created by Tombrello in presenting him the inaugural teaching award: Physics 11, a research tutorial that allows freshmen to design and pursue their own research projects, and Physics 10, Frontiers in Physics, which teaches freshmen and sophomores about physical-science research on campus. "The format that Tom created, of having a guest professor describe his research in one lecture and then having the course instructor reiterate, expand, explain it, and answer any questions that pop up, in the next meeting, is truly stimulating for the students," noted then division chair Charles Peck, "and is yet another example of Tom's deep commitment to teaching." e&s

Alumni to Students: **Yes, There**

By Ramanuj Basu

Tsunami research. The halls of Congress. The future of nuclear power. Penguin propulsion. What do these things have in common?

They're all topics of conversation overheard at a recent Life After Caltech event presented by the Caltech Alumni Association. The program is designed to help current students hear from successful alumni in various fields, each of whom has taken a unique path following graduation from Caltech.

Former Facebook chief technology officer Adam D'Angelo (BS '06), in the brown T-shirt, proves that there is, indeed, Life After Caltech.

New this year, Life After Caltech brings alumni back to campus to connect with small groups of students over a shared meal at Caltech's Alumni House. A typical event finds an alumnus and about 10 students, both undergraduate and graduate, around the dining-room table. Founder and CEO of abInventio Alex Bäcker (PhD '02) was the guest for the inaugural event in February, with succeeding events featuring entrepreneurs and philanthropists Ken and Gabrielle Adelman (BS '86 and '87, respectively); lawyer Timothy Yoo (BS '04); technology entrepreneur Jim Fruchterman (BS and MS '80); and cofounder of Quora and former Facebook CTO Adam D'Angelo (BS '06).

These events aren't formal presentations by the alumni, and those attending aren't simply a captive audience. There's no PowerPoint; there's not even a computer in sight. The talk is general (thus the foray into penguin propulsion), and that's a big part of the appeal. After brief remarks by the guest of honor, the conversation flows and anything is fair game. Often the talk shifts from discussions of career paths to another shared topic of interest: life *at* Caltech. "What was it like when you were here?" is a frequent question, and alumni provide a unique perspective, living "out there" but anchored by their Caltech experience.

A recent attendee commented, "We're very sheltered at Caltech, and it's very helpful to get 'reality checks' from people in the 'real world' from time to time." Here's a sampling of sound advice from alumni who've "been there, done that," culled from recent gatherings:

Often the talk shifts from discussions of career paths to another shared topic of interest: life at Caltech. "What was it like when you were here?" is a frequent question, and alumni provide a unique perspective, living "out there" but anchored by their Caltech experience.

- Thinking about a career in business? Heed this: "You know you're good at *research*, but business is all about people. You have to be able to read *people*."
- Want to pitch an idea or a funding proposal? "Go to the guy at the top. Get the president or CEO to buy in." Sometimes doing it old-school is best: "Go meet people. Knock on doors."

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is Life After Caltech!

- Hoping to launch a start-up? "It's difficult to start a company right out of college because you've never done anything." However, "Working at a start-up is a great way to learn."
- Want that to be an online service? "In order to get good at Internet products, you have to build a bunch of things for fun!" and then "Invite 200 friends, let them invite others, grow into an insiders' club, then open it up."

Two events in the series have featured several alumni guests each. Last March, students had the chance to sit and talk with members of the Caltech Alumni Association's all-volunteer board of directors. About 40 students signed up to join one alum for lunch at a small table, then mingle with the other alumni after the meal in a scene reminiscent of speed dating.

The same format was used in June's "Postdoc Special Edition" of Life After Caltech, when postdoctoral scholars from Caltech and JPL sat and chatted with alumni from a variety of fields during an alfresco dinner at Alumni House. And, proving that sage advice doesn't come just from the alumni, a postdoc chimed in to suggest to other attendees, "If your proposal is turned down, call and ask for feedback."

What do the participating alumni get out of the program? After June's event, Bassil Dahiyat (PhD '98), cofounder of Xencor, remarked, "I enjoyed reconnecting with Caltech people, and regained perspective on what it is like for those finishing up their training." Those sentiments were echoed by Nicola Peill-Moelter (MS '93, PhD '97), now director of environmental sustainability at Akamai Technologies, who said, "I very much enjoyed spending time with the students and hearing about all the exciting things they are working on." And as the evening wrapped up, alumnus Phil Watts (PhD '97) leaned over to an attendee and said, "You and I have a lot of common interests. I'll get your number and we'll keep in touch."

The Caltech Alumni Association's mission of "strengthening the ties of goodwill and communication between the Institute, its alumni, and its students" is well-served by the Life After Caltech series and a wide variety of other Association activities and services. Alumni who would like to get involved on campus or in their local communities should drop a line to volunteer@alumni.caltech.edu.

Ramanuj Basu (BS '84) is the Associate Director for Alumni Relations Communications.

Join the Caltech Alumni Association Group on LinkedIn and connect with nearly 5,000 alumni, students, and postdocs.

W. BARCLAY KAMB

1931–2011

Kamb, an accomplished photographer, took this shot of Keith Echelmeyer exploring a hundred-foot-deep Antarctic crevasse.

W. Barclay Kamb, the Rawn Professor of Geology and Geophysics, Emeritus, died at his home in Pasadena on April 21, 2011. He was 79.

Kamb, one of the world's leading glaciologists, determined the crystal structure of all the known phases of ice and studied the dynamics of glacier movement. A rugged outdoorsman, he developed and maintained an intellectually and physically challenging field program on glaciers around the world, devising new techniques for making technically difficult measurements under extreme conditions in places like Alaska and Antarctica.

Born in San Jose, California, in 1931, Kamb began his Caltech career in 1948 as a 16-year-old freshman. He earned a BS in physics in 1952 and a PhD in geology in 1956. Hired upon graduation as an assistant professor of geology, Kamb rose through the ranks to become a full professor in 1962 and Rawn Professor in 1990. He served as chair of the Division of Geological and Planetary Sciences from 1972 to 1983, and as vice president and provost from 1987 to 1989.

"I can say with absolute certainty that were it not for Barclay Kamb, I would not be at Caltech," says provost Ed Stolper, the Leonhard Professor of Geology and one of 10 faculty members in the division hired during Kamb's time as chair. "He was more than a mentor—he epitomized the Institute. His willingness to serve was an inspiration: He was asked on a few days' notice to become provost, after having already completed more than a decade as division chair, and he did not blink. His truly extraordinary intellect and focus; his understanding of the importance of field work interpreted in a rigorous physical, chemical, and mathematical framework; and his commitment to the division and to the Institute all taught the cohort that he hired what was so special about Caltech and about our responsibility to preserve it."

Kamb's interest in the physical sciences was broad. Although he began his graduate studies as a physics student, a strong love of the outdoors and the influence of geology professor Bob Sharp (BS '34, MS '35)—who had been named by *Life* magazine as one of the 10 great U.S. college teachers of 1950—changed his course. Kamb also became interested in mineralogy and X-ray crystallography, doing his PhD thesis on the structure of the complex mineral zunyite under the direction of Nobel laureate and professor of chemistry Linus Pauling (PhD '25). Pauling not only regarded Kamb as his best student, he introduced him to his only daughter, Linda. In 1957, a year after earning his PhD, Barclay and Linda were married. By 1965, they were the proud parents of four sons.

"My brothers and I were fortunate to grow up as part of the Caltech family," says son Alexander (Sasha) Kamb (PhD '88). "We used to walk over after school and kick around my father's back office among the rocks, minerals, and maps. And we were passive participants on Caltech-sponsored outdoor trips, like geology field camp in the Sierra Nevada Mountains, and expeditions to the Blue Glacier up in Washington. These experiences helped to mold us and rank among my fondest memories of him."

Sasha says that beyond his father's gifts for math and science, he wrote beautifully, sketched like a professional artist, fixed cars, built houses, spoke multiple languages, and played three instruments. "But most impressive to me, in the face of all the evidence to the contrary, he thought he was just like everybody else," he says.

Kamb first made his name in glaciology at the Blue Glacier on Mount Olympus in Olympic National Park, Washington, where he directed Caltech's research program for over 10 years. From Washington, Kamb moved on to the glaciers of Alaska, where he pioneered the use of high-pressure hot-water jets to drill through the ice all the way to the hitherto inaccessible bottom. He also developed methods for taking samples and images of the contact between the glacier and the underlying bedrock.

Many of the borehole instruments were one-of-a-kind devices, designed by Kamb and built from scratch in the machine shop at Caltech. "Barclay did not like black boxes," says glaciologist Hermann Engelhardt, a senior research associate, emeritus, who collaborated with Kamb for over 45 years. "He needed to understand every detail of his instruments down to the tiniest screw."

The hot-water drill Kamb and Engelhardt developed debuted in 1982 on Alaska's Variegated Glacier in "the first detailed study of a surging glacier during its active period," according to Engelhardt. This galloping glacier was moving as much as 65 meters per day, over 300 times its normal pace, "with high-pitched ice quakes and new crevasses opening overnight under the sleeping tents and the drilling platform. The ice accumulation of 20 years was swept through the valley in just three months." In those days before GPS, the flow was monitored by hand with a theodolite and a network of surveyors'

Kamb surveys Alaska's Variegated Glacier in 1993. Crevasses can open anywhere during a surge; this one just missed the survey stake, and was still slowly growing.

PICTURE CREDITS:
40, 41, 43 — Kamb family

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VISA

stakes equipped with radio-controlled lights for nighttime measurements. "Barclay called it his Christmas tree," Engelhardt recalls.

In 1988, Kamb began the Antarctic Project, which ran for 12 summers and yielded "a seminal series of papers in *Science* and *Nature*" while training over 100 field assistants, including grad students and postdocs from around the world. "Antarctica is the coldest and windiest and remotest place on Earth, and the base of the ice is certainly the remotest destination in Antarctica. Only Barclay had the vision, the stature, and the courage to launch such an ambitious project—to go where nobody had gone before and study the basal conditions of the biggest glaciers on Earth," says Engelhardt.

Kamb focused on the ice streams in the West Antarctic Ice Sheet that empty into the Ross Ice Shelf, a floating expanse roughly the size of France that projects out into the Ross Sea. "An ice stream is like a current in the ocean," explains Engelhardt. "It's a fast-moving current of ice in an ice sheet." Over the years, the team drilled hundreds of boreholes as much as 1,600 meters deep to reach the base of the ice streams.

Since the boreholes were water-filled, each one was a race against refreezing. "Instruments had to be inserted quickly, or when taking videos from the base of the ice, the downhole working time was limited to guarantee the safe return of the camera," Engelhardt recalls.

The drilling confirmed what Kamb had discovered in Alaska—the ice streams' rapid movement was made possible by a lubricating layer of high-pressure water between the ice and the bedrock below. Kamb's work also implies that in a warmer climate, fast-moving ice will speed up due to increased lubrication. "A glacier is a very good instrument to monitor climate change," says Engelhardt. "In Alaska we see the surge cycle getting shorter and shorter, and tidewater glaciers disintegrating."

Kamb also found that the till—the deposits of clay, sand, and gravel beneath the ice that have been carried downstream by the glacier—"contained an abundance of diatoms, showing that West Antarctica was an open ocean in the recent Pleistocene [about 12,000 years ago]," Engelhardt says. "This happened under CO_2 concentrations in the atmosphere much lower than today. Barclay's results could not speak louder and clearer that the catastrophic decay of the West Antarctic Ice Sheet is a real possibility, with a consequent sea-level rise of some six meters, if climate change is not taken seriously and reversed responsibly."

Kamb was a fellow of the Geological Society of America and the American Geophysical Union, and was a member of the American Academy of Arts and Sciences and the National Academy of Sciences. His many honors included a Sloan Research Fellowship, a Guggenheim Fellowship, and the Mineralogical Society of America Award. In 1977, he won the Seligman Crystal, the highest award in glaciology presented by the International Glaciology Society. And in 2003, the American Advisory Committee on Antarctic Names formally designated Ice Stream C, the central stream flowing into the Ross Ice Shelf, the Kamb Ice Stream.

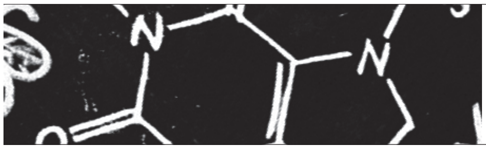
Kamb is survived by his wife, Linda Pauling Kamb; his brother, Peter Ray, and his sister, Barbara Marinacci; his sons, Barclay, Alexander (Sasha), Anthony, and Linus; and nine grandchildren.

—KN/DS E&S

The Kamb family poolside in the backyard, circa 1978. From left: son Anthony; Kamb; wife Linda; twins Alexander (Sasha) and Barclay; and, in front of them, son Linus.

WE ASKED CALTECH ALUMS FOR THE ONE PIECE OF ADVICE THEY'D GIVE AN INCOMING FRESHMAN. HERE'S WHAT THEY HAD TO SAY:

Enjoy your sip from the fire hose.



Go to all lectures by famous visitors.

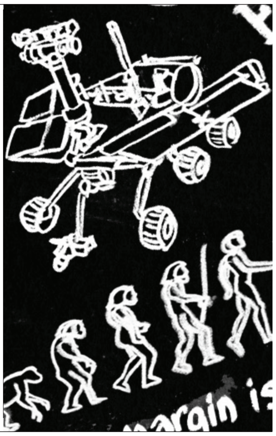
Go to sleep whether or not your homework is complete.

Take advantage of opportunities outside the classroom: educational, social, and artistic.

Get acquainted with as wide a cross-section of the Caltech community as possible—faculty, grad students, lab technicians, everyone.

Diversify your curriculum—you will probably change your major or your field later in life.

After graduation, if given the opportunity to go on a trip to somewhere far away, go. Do not put it off thinking, "I can do this later."



Don't judge a college by its football team.

Don't lose sight of who you were before you came here.


BECKMAN INSTITUTE

Engineering & Science

California Institute of Technology
Pasadena, California 91125