e&s

Engineering & Science

IN THIS ISSUE:

Volcanoes and Earthquakes ▪ Zombies and Celebrities ▪ Aggression and Fruit Flies

VOLUME LXXIII, NUMBER 4, FALL 2010

California Institute of Technology

ON THE COVER

Teaching a computer how to spot you in a crosswalk could be a first step toward teaching it how to figure out what you're thinking. From left: Postdocs Piotr Dollar and Michael Maire and professors Pietro Perona and David Anderson put the Caltech Pedestrian Detector through its paces. (The number in each box measures the computer's confidence that the object in the box is a person.) But since humans are so complex, the researchers are starting small—turn to page 25 to find out *how* small.

TEDx CALTECH—JANUARY 14, 2011

Raconteur, visionary, artist, Nobel laureate, and self-proclaimed "curious character" Richard Feynman will get the TED treatment on January 14. TED conferences are organized around "ideas worth sharing" and operate according to a full-throttle format in which each speaker has 18 minutes to "give the talk of their lifetime."

TEDxCaltech celebrates the 50th anniversary of Feynman's prescient talk, "There's Plenty of Room at the Bottom," published in these very pages, and the classic *Lectures on Physics* by taking a look at what the next 50 years might bring. The day will offer an eclectic mix of music and art, as well as science on scales from the quantum to the cosmic. Here's a sampling of the more than 30 presenters:

ANGELA BELCHER, a MacArthur "genius" who uses viruses to engineer environmentally friendly materials and was named one of *Rolling Stone*'s "100 People Who Are Changing the World" in 2009. Physicist **DON EIGLER**, who helped open the nanotechnology era in 1989 by spelling out the letters "IBM" with 35 xenon atoms under a scanning tunneling microscope. **ERIC HELLER**, a chemical physicist whose digital renderings of quantum chaos are sold as fine art. **CHARLIE MARCUS**, a builder of actual nanoelectronics and theoretical quantum computers. Jazz pianist and composer **LYLE MAYS**, cofounder of the multi-Grammy Pat Metheny Group. Tuvan throat singer **KONGAR-OL ONDAR**. Synthesizer programmer and sound designer **BOB RICE**, who has worked with musicians from Michael Jackson to Frank Zappa. String theorist **LEONARD SUSSKIND**. Cosmologist **ALEXANDER SZALAY**. Documentary producer **CHRISTOPHER SYKES**, whose PBS profiles of Feynman include *The Pleasure of Finding Things Out* and *The Best Mind Since Einstein*. **J. CRAIG VENTER**, who in 2001 was among the first to sequence a human genome (his own) and in 2010 helped create the first "synthetic" life form—a cell with a hand-assembled genome. And, of course, there will be Feynman stories, told by two of his colleagues: **JOHN PRESKILL** and **KIP THORNE** (BS '62).

Emcee **RIVES**, who co-hosts the annual TEDActive conference in Palm Springs, will be flipping speakers like flapjacks. Rives is a poet and designer of pop-up books who, in 2008, tooled around the country with Israeli supermodel Bar Refaeli in a red '67 Cadillac El Dorado convertible for Bravo TV's *Ironic Iconic America*. Bar, alas, will not be joining us, but the audience will have ample opportunity to mingle and connect with the speakers during the coffee breaks, at lunch, and at the closing reception.

The sessions run from 10:00 a.m. to 6:30 p.m. in Caltech's Beckman Auditorium, with on-site check-in beginning at 8:00 a.m.; the doors open at 9:30. There are no breakout groups, so you're guaranteed not to miss a thing. Leave your laptops, cell phones, and other electronic umbilicals in the car—you won't have the time or the inclination to turn them on, anyway.

Registration ($25 for Caltech students; $65 for Caltech faculty, staff, postdocs, alumni, and JPL employees; and $85 for all others) includes all food and beverages—from the all-day complimentary espresso bar on through the reception. Sign up now at http://tedxcaltech.com/. —*DS* E&S

Engineering & Science is printed on recycled paper containing a minimum of 10 percent postconsumer waste. The paper's virgin pulp comes from trees grown in the U.S. in accordance with the Forest Stewardship Council's sustainability standards.

VOLUME LXXIII, NUMBER 4, FALL 2010

e&S
Engineering & Science

Engineering & Science (ISSN 0013-7812) is published quarterly at the California Institute of Technology, 1200 East California Boulevard, Pasadena, CA 91125. Annual subscription $20.00 domestic, $30.00 foreign air mail; single copies $5.00. Send subscriptions to Caltech 1-71, Pasadena, CA 91125. Third-class postage paid at Pasadena, CA. All rights reserved. Reproduction of material contained herein forbidden without authorization. © 2010, California Institute of Technology. Published by Caltech and the Alumni Association. Telephone: 626-395-3630.

Visit us online at **http://EandS.caltech.edu** for videos and web links.

PICTURE CREDITS
Cover — Bill Youngblood and Piotr Dollar; 2 — Doug Smith; 2-3 — Bill Youngblood; 2-3, 23 — NASA/JPL-Caltech; 4 — Thomas Mitchell; 5 — Sally Bane and Joseph Shepherd; 6-8 — Caltech Archives; 7 — NASA/JPL/USGS; 9 — David Prober Lab, Chau Dang; 10 — Brad Whitmore/STSci/NASA; NASA/JPL/Caltech/Z. Wang (Harvard-Smithsonian CfA), M. Rushing; CSO; 11, 12, 41 — Bob Paz; 12 — Jamie Bock and Anthony Turner, JPL; 13 — Tim Pyle; 16, 19 — Doug Cummings; 16 — Bob McNeely, courtesy of The White House; 17 — Ray Tamarra/Getty Images; 20 — NASA's MODIS Rapid Response Team; 21, 24 — Heidi Aspaturian; 22 — USGS; 25 — Eric Hoopfer; 26 — Yue Shen; 27 — Bill Youngblood and Doug Cummings; 35 — NASA/ESA and Mike Brown; 42, 43 — Caltech

Thomas Lloyd
President of the Alumni Association

Peter D. Hero
Vice President for Development and Institute Relations

Kristen Brown
Assistant Vice President for Marketing and Communications

STAFF
Editor
Douglas L. Smith

Writer
Marcus Y. Woo

Contributing Writers
Paula DiConti, Barbara Ellis, Michael Farquhar, Lori Oliwenstein, Jon Weiner, Ann Wendland

Copy Editors
Sara Arnold, Paula DiConti, Barbara DiPalma, Michael Farquhar

Business Manager
Rosanne Lombardi

Graphic Artist, Layout
Doug Cummings Design

OPERATION: MARS ANTENNA

In a marriage of brute force and millimetric precision, a vital communications link in the Deep Space Network has just undergone a major repair. The giant Mars dish—so named because its first job, in 1966, was to track Mariner 4 after its flyby of the red planet—has relayed commands to, and data from, every earthly emissary to have ventured beyond the moon. As the most sensitive antenna available, it was also crucial in bringing the Apollo 13 astronauts home. But 44 years of operation—more than double its projected 20-year lifespan—have taken a toll on the bearings that allow it to aim its radio beam precisely at a spacecraft the size of a VW Beetle more than 10 billion kilometers away.

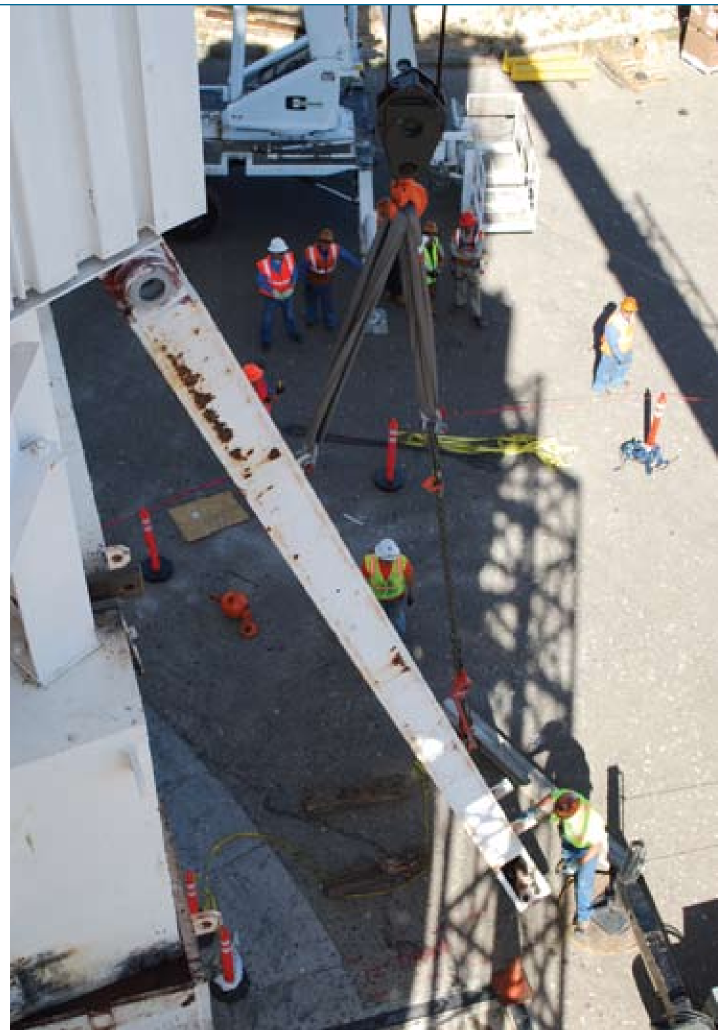
Officially known as Deep Space Station 14, the 70-meter antenna sits in a shallow valley at JPL's Goldstone complex deep in the Mojave desert between Los Angeles and Las Vegas, where it is shielded from as many of humanity's interfering radio signals as possible. The dish and its substructure, including the two-story corrugated steel building that houses the drive motors and some of the signal-processing equipment, weighs about 3,000 metric tons—more than a herd of 500 elephants.

The entire assembly, as tall as a 20-story building, rests on three steel support pads. These pads are part of the hydrostatic bearing on which the antenna rotates, and they glide on a quarter-millimeter film of oil atop a 24-meter-diameter steel ring called the runner. The runner, in turn, sits on a 10-meter-tall pedestal. Tiny trickles of oil would seep through the runner's joints and drip off its edges, deteriorating the cement-based grout below. As the grout softened, the runner would develop "waves," so a team of four technicians would spend eight to 10 hours a week inserting shims under the runner to keep it level.

Work began in March to replace the runner, the grout, and the elevation bearings that allow the dish to tilt from the zenith to the horizon. The elevation bearings were done first—a sort of warm-up job, as this merely involved lifting 1,800 tons of dish off its mounting. Next, the crew used the same hydraulic jacks to raise the entire 3,000-ton colossus five millimeters—enough clearance to ease out the old components and install a thicker runner with tighter joints on new oil-resistant, epoxy-based grout.

As it talks to far-flung spacecraft, the Mars dish also measures the distance to them, providing vital data to the navigation teams. Changing the dish's height by more than a few millimeters would void these calculations. The new runner is seven inches thick to the old runner's five, so, in one final engineering challenge, the hydrostatic bearing pads had to be removed and machined down to compensate.

The project, two years in the planning, had a set-in-cement deadline: the dish had to be back on line by early November, in time for JPL's rendezvous with comet Hartley 2. They made it. —*MW/DS* E&S



OPPOSITE PAGE

Top left: Sometimes low-tech fixes keep high technology in business. Stainless steel shims, fabricated to an accuracy of 0.0001 inches, keep the runner level.

Top right: One of the three hydrostatic bearing pads that slide along the runner as the giant antenna rotates on its pedestal.

THIS PAGE

Top left: A crane lifts one of 11 new runner segments to the top of the concrete pedestal. Once there, segments were maneuvered into position on air bearings, on which they floated like pucks on an air-hockey table.

Top right: JPL engineer Tim Sink checks the levelness of the sole plates that will support the runner segments. The laser leveling was done in the cool of the night to minimize any thermal-expansion errors due to the July heat. The grout was mixed and poured at night for the same reasons. With daytime highs routinely over 100 degrees Fahrenheit, the night shift was a plum assignment.

Middle left: Removing the hydrostatic bearing's pads was as easy as opening a kitchen drawer—if your drawers weigh 6,400 kilograms each, that is.

Middle right: Workers prepare to install one of the three support legs that took the weight of the antenna once it had been jacked up off the runner.

Right: JPL's EPOXI mission took this look back at comet Hartley 2 on November 5 at a distance of 849 kilometers. The comet's nucleus is about two kilometers long and about 0.4 kilometers wide at the "neck" in the middle. Hartley 2 is the smallest, most active comet yet visited by a spacecraft, and EPOXI's observations are the most detailed yet made. The jets appear to be a mixture of carbon dioxide and dust, suggesting that chunks of dry ice in the comet's interior are vaporizing from the sun's heat.

HAVING A BLAST

In 2007, soon after landing at Naha Airport on the island of Okinawa in Japan, a Boeing 737 started spewing fuel from a puncture in its right-wing tank. As the fuel flowed onto the hot engine, it ignited, causing several explosions as flames engulfed the plane. Fortunately, everyone evacuated in time and no one was hurt.

Of course, planes, trains, and automobiles don't generally burst into huge fireballs whenever they're near a heat source, whether it be a spark or a lit cigarette—despite what Hollywood might lead you to believe. But clearly, exploding fuel is a hazard, and understanding how it ignites allows engineers to develop the proper safety regulations to minimize danger.

Postdoc Sally Bane (PhD '10), working with Joe Shepherd (PhD '81), Johnson Professor of Aeronautics and professor of mechanical engineering, is analyzing how a spark can ignite flammable gas. She's discovered that these spark-ignited explosions are a lot more complicated than previously thought, and her results bring much-needed updates to safety standards that are decades old—and, in some cases, based on data that are flat-out wrong.

For decades, engineers have determined the likelihood of a spark-ignited explosion in an aircraft by using a number called the minimum ignition energy (MIE). Each type of fuel or vapor has its own MIE value, and if a spark's energy is below that value, then nothing should ignite. The problem, however, is that the MIE is based on data from old experiments, some from more than 60 years ago. Even though the numbers have been updated over the years, no one has ever gone back and reevaluated the original experiments in depth. The original data from the 1940s are still cited today, Bane says.

As an expert in explosions, Shepherd was recruited in 1996 by the National Transportation Safety Board to help figure out why TWA Flight 800 crashed into the Atlantic just 12 minutes after takeoff from New York's JFK Airport (see "Learning from a Tragedy," *E&S* No. 2, 1998). During the investigation, some of Shepherd's experiments showed unforeseen variability in spark-ignited explosions—even with a spark below the MIE, the fuel sometimes still blew up. However, he didn't get a chance to explore the issue further until Bane came to his lab as a graduate student in 2005.

According to Bane, performing this kind of experiment is difficult and time-consuming, and since there hadn't been any obvious reason to doubt the old MIE data, people were content with the existing information. It took her five years to design, build, and run her experiments, which are among the most rigorous ever done.

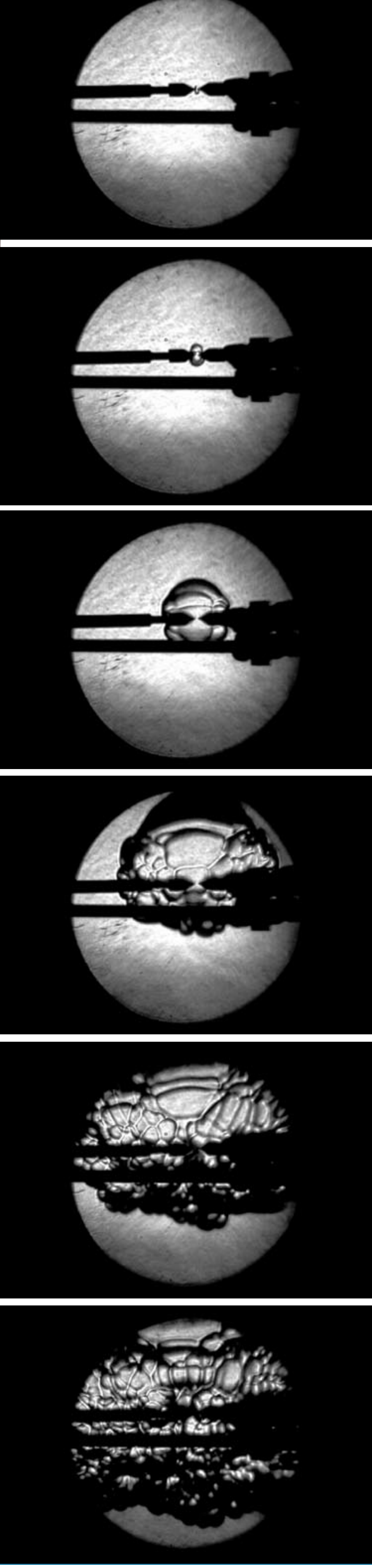
Her explosions range from harmless puffs to tiny fireballs, safely contained in a solid-steel vessel weighing 200 kilograms. Inside the vessel are two pointy tungsten electrodes, separated by a couple of millimeters. Charge builds up in the electrodes, generating a voltage difference that ionizes the gas between them. The ionized gas creates a path for electrons to travel from one electrode to the other, and in just a few nanoseconds, you get a spark. The spark energies that Bane works with are relatively low—as low as 50 microjoules. You would need a million of these sparks to light a 50-watt lightbulb for a second.

A high-speed camera, which can take up to several hundred thousand frames per second, records the spark and any resulting explosion. Bane repeated the experiment for different spark energies and with various mixtures of flammable gases as suggested by the Aerospace Recommended Practices, standards developed by the Society of Automobile Engineers that guide the design and production of aircraft parts. The mixtures contained 5, 6, or 7 percent hydrogen, oxygen, and argon.

Unlike tests that are common in the industry, Bane's are done in a sealed vessel, which means that she knows the gas's composition, temperature, and pressure with a high degree of certainty. Furthermore, Bane says, in other setups, there's no camera that directly observes the ignition. Instead, the only way to tell that there's been an explosion is to watch whether a piece of foil, which is across an opening in the vessel, pops up—or, if the blast is violent enough, bursts open.

Bane discovered that there isn't a single MIE value for a given flammable mixture; there's no single energy that sets the threshold for whether an explosion is possible. Instead, she found, whether or not a certain spark ignites the gas is an exercise in probabilities, rising and falling with the energy of the spark. To be sure, at some point, the energy is too low and an explosion is impossible. But it's not as cut and dried as people had thought.

In the case of the 7 percent hydrogen mixture, Bane's results were roughly comparable to the



Far left: The aftermath of the fire that engulfed a Boeing 737 when leaking fuel was ignited by a hot engine. Fortunately, no one was hurt.
Left: A spark between the two pointy electrodes ignites the 7 percent hydrogen mixture, generating a fireball. It's not as dangerous as it looks—the explosion is small. For comparison, the distance between the electrodes is only a few millimeters. The snapshots are taken at 5, 50, 100, 175, and 250 microseconds.

experiments done by Bernard Lewis and Guenther von Elbe in the 1940s, which gave an MIE of 100 microjoules. She found that at 100 microjoules, the gas had a 10 percent chance of igniting. But for the 5 percent hydrogen mixture, the MIE given was 200 microjoules, while Bane determined that the spark had to be at least 780 microjoules before it even had a 10 percent chance of blowing up. It turned out that Lewis and von Elbe hadn't actually had data for a 5 percent hydrogen mixture back in the 1940s—they had just extrapolated the MIE from data for the 7 percent gas.

This variability is likely an inherent characteristic of spark ignition, Bane says. Even when she kept the conditions as constant as possible, the explosions were never consistent. The spark itself—the channel of plasma connecting the two electrodes—is intrinsically irregular, wavering in shape and motion. Other complexities have been revealed in fluid-dynamic simulations that Bane and graduate student Jack Ziegler have run of the ignition process.

Bane and Shepherd are now working to develop better safety standards with Boeing, which funded the research. Last summer, she expanded her experiments to include kerosene, the type of fuel used in most commercial aircraft. Unlike clean-burning hydrogen, kerosene is a dirty fuel, so after each trial, Bane dons a protective jacket, Kevlar gloves, and goggles before opening the hot vessel to swab out the soot and set up the next experiment.

Bane is finding that it doesn't take much energy to set off kerosene. She was able to ignite kerosene at 60 degrees Celsius with only 0.65 microjoules, while in Shepherd's previous work, it took 40 microjoules to ignite the fuel at 52 degrees. "I anticipate that in future tests I'll be able to ignite mixtures with even lower energies," she says. The ignition of fuel vapor is highly sensitive to temperature change, Bane explains, and her experiment used shorter-duration sparks—about a couple hundred nanoseconds, which is a more accurate simulation of an electrostatic discharge—so the discrepancy isn't a complete surprise. But the fact that it's apparently much easier to ignite kerosene than the test mixtures specified by the FAA has certainly gotten the attention of the folks at Boeing.

Bane says her data can be applied to any situation where there's a tank of fuel and the possibility of a spark—for example, in power plants, in the natural-gas tank that heats your house, or when storing hydrogen gas, which has garnered interest as a clean-burning fuel. But as for smoldering cigarettes blowing cars to kingdom come? "That could never happen," Bane says. Gasoline needs to be extremely hot to ignite, and a cigarette just won't cut it. But it sure looks cool. *—MW* e&s

Watch Sally Bane discuss her work as part of the 2010 Everhart Lecture Series.

A map of the world—or rather the parts the Romans knew or had heard about in 150 CE—from Claudius Ptolemy's *Geographia*.

ON THE MAP

From Neolithic cave painting to Google Earth, humans have used maps to depict, understand, and navigate their environment. Now some of the Caltech Archives' finest treasures on the subject of mapping the earth, the skies, and longitude have gone on display, many for the first time, on the second floor of Parsons-Gates Hall of Administration. The *On the Map* exhibit includes Claudius Ptolemy's 2nd-century map of the known world; Georg Braun and Frans Hogenberg's beautifully illustrated *Civitates Orbis Terrarum*, from the latter part of the 16th century; a 1570 map of Russia by Abraham Ortelius; Johannes Bayer's 1603 *Uranometria*; Johannes Kepler's world map of 1627; a 17th-century planispheric celestial map by Andries van Luchtenberg; prints from Joan Blaeu's 1662 *Atlas Maior*; and first editions of books by Tycho Brahe, Johannes Hevelius, Giovanni Domenico Cassini, and Christiaan Huygens.

Ptolemy's map is an early 16th-century version reconstituted from his cartography and geography book, the *Geographia*, published in 150 CE. Ptolemy, a Roman citizen of Alexandria, knew that the earth was a globe—the ancient Greeks had worked it out centuries earlier—but his view of the world extends only from the zero-degree line of longitude off the west coast of Africa (beyond which no sailor had returned to tell the tale) to the 180-degree line through China, and from 60 degrees north latitude to 30 degrees south. He omitted the three-quarters of the globe that was still uncharted, a technique that humans still employ today when mapping unknown terrain such as Saturn's moon Titan, currently under surveillance by JPL's Cassini spacecraft. Cassini's radar views a narrow swath of Saturn's lunar companion with each flyby, and the resulting maps, in which Titan's topographical features are interspersed with black regions for which no data exists, are in some sense Ptolemy's intellectual descendants—JPL's cartographers don't fill the empty space with creations of their own fancy.

Cassini will, in all likelihood, map Titan more rapidly than humans mapped the earth: the Americas, after all, were not discovered by Europe until the late 15th century. But once the Age of Exploration got under way, the exciting accounts of new lands brought back by sailors sparked a renewed interest in geography among prosperous and literate Europeans. Printing presses, invented a few decades earlier, found a lucrative market in catering to the demand for information.

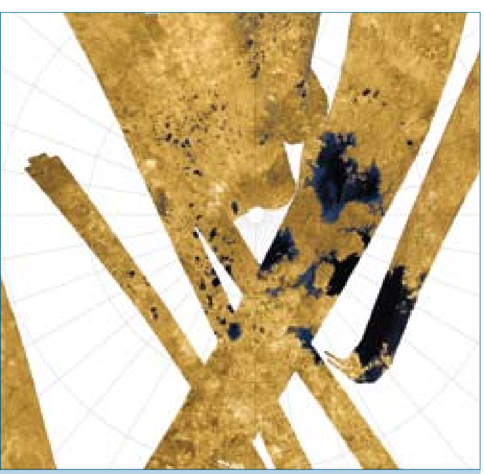
In 1513, the German cartographer Martin Waldseemüller, whose large map of the world (and the first map to use the name "America") had sold well a few years earlier, decided to bring out Ptolemy's *Geographia*. For centuries the Christian world had regarded the ancient geometer as a heretic, and the work was hidden away and forgotten until its rediscovery in the 14th century. Waldseemüller borrowed a manuscript copy, in Greek, from an Italian monastery. The maps were missing, but he reconstituted them, including the world map in the Caltech display, from Ptolemy's extensive topographical list—a compendium of place names and geographical features along with their latitudes and longitudes. (The list was compiled from travelers' reports, and many of the longitudes were wrong—

Anyone comparing a current map of Basel with this 1575 view from Braun and Hogenberg's *Civitates Orbis Terrarum* ("Towns of the World") might think that the Rhine has changed its course over the years. But what's really changed is our notion that maps always have north at the top. In the 16th century, there was no convention for map orientation, and this view is from the north looking south. A compass rose to guide the viewer was also considered unimportant.

or, at best, very bad guesses—which is why the landforms get increasingly distorted the farther one gets from the Mediterranean.)

In the decades that followed, decorative maps and atlases found ready buyers. Some of the finest were produced by the Flemish cartographer Abraham Ortelius, who pioneered the change from the woodcut printing of maps to copperplate engraving, with italic lettering and rich hand-coloring that greatly enhanced the definition and beauty of the prints. When his *Theatrum Orbis Terrarum* ("Theater of the World"), the first true atlas, sold well, he encouraged Georg Braun and Frans Hogenberg of Cologne to produce a companion book of town views and history, the *Civitates Orbis Terrarum* ("Towns of the World").

With its first volume published in 1572, Braun and Hogenberg's ambitious project took an additional 45 years to complete, and Caltech is fortunate to own four volumes from



Cassini made this radar mosaic of Saturn's moon Titan. The surface is covered in seas, tinted blue and black.

the six-volume first edition. Their scrupulously detailed town plans generally depict buildings and houses from a bird's-eye perspective and are brought to life with drawings of people in local costume carrying out their trades, of animals, and of scenes from history, all accompanied by an account in Latin of the town's situation, population, history, government, commerce, and traditions.

Today the "armchair traveler" has morphed into the "Google Earther," as more and more people turn to cyberspace to swoop in on houses or the world's cities. Interestingly, Wikipedia's city pages provide almost the same information that Braun and Hogenberg did.

Humans were likely curious about the heavens even before they explored the world: following the daily course of the sun, moon, stars, and planets doesn't involve any traveling. Early astronomers and geographers both used the same surveying instruments, such as quadrants and astrolabes; and both earth and sky maps have equators and poles, latitude and longitude. (The longitude of a star or planet is given by its right ascension, while the latitude is given by its declination.) For millennia, star tables—celestial topographical lists—played an indispensible role in predicting important events in the calendar such as equinoxes, solstices, phases of the moon, and eclipses (not to mention their use in casting horoscopes!), but they were so imprecise that, according to the young Tycho Brahe, "There are just as many measurements and methods as there are astronomers, and all of them disagree."

Accordingly, Tycho (as he is commonly known), a Danish nobleman, made it his life's work to take accurate, systematic observations from a single spot over many years. He persuaded King Frederick II of Denmark to give him the small island of Hven (modern Ven), in the straits between Denmark and Sweden, and to build him an observatory there and provide him with a generous income to fund it. Today's astronomers should be so fortunate!

Tycho named his palatial astronomical research center Uraniborg, the Castle of the Heavens. With accommodations for up to a hundred observers, assistants, and visiting scholars, it was not unlike a modern astronomical research center, save for the alchemy workshop in the basement and the utter lack of telescopes (Tycho was the last major astronomer to survey the skies entirely by naked eye.) He later added Stjerneborg, the Castle of the Stars, an underground observatory with a rotating dome that sheltered his instruments from the buffeting winds that swirled around Uraniborg's towers. A series of lakes provided waterpower for both instrument workshops and a mill that produced paper for publications. Unfortunately, after Frederick's death, Tycho argued with his heir and had to abandon the island in 1597.

Uraniborg, Stjerneborg, and the lakes can be seen on the map of Hven in the Archive's display—a reproduction of a colored engraving by Willem Blaeu from Joan Blaeu's *Atlas Maior*, 1662. The young Willem,

A map of Tycho Brahe's island of Hven (now Ven) from Joan Blaeu's *Atlas Maior* of 1662, showing the observatories Uraniborg and Stjerneborg and the lakes that provided waterpower.

Joan's father, had studied astronomy and globe-making with Tycho, and he went on to run a successful map-publishing business in Amsterdam. Uraniborg was demolished shortly after Tycho's sudden death in 1601, but today we can zoom in on Ven via Google Earth and view Uraniborg's partially restored gardens, the remains of Stjerneborg, and even, faintly, the remains of the lakes.

Tycho's assistant, Johannes Kepler, who would go on to attain some fame in his own right, finished the work by preparing a new set of star tables based on the Hven observations. These he published in 1627 as the *Tabulae Rudolphinae*, or "Rudolphine Tables," in honor of Rudolf II of Austria, Holy Roman emperor and Tycho's royal patron at the end of his life, and Kepler's patron as well. The exhibit includes a photograph of a large world map folded inside Caltech's copy of the *Tables*. The map's unusual projection, comprising one whole hemisphere centered on Europe and Africa, flanked by two half hemispheres, was Kepler's own design. It was probably intended to make it easier for navigators to plot their position by keeping the most-traveled seaways of the Known World contiguous. Kepler's line of zero longitude is centered on Hven. Caltech is fortunate to have this map, as it is rare: the engraver had not finished it when the book was published, and after the astronomer's death three years later, it lay forgotten until rediscovered in 1658.

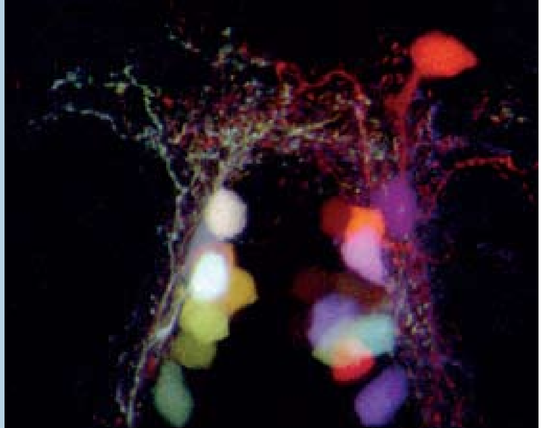
Kepler also tackled the problem of accurately measuring one's longitude, a necessity for any maritime power attempting to become a global presence. But although his method gave useful results on dry land, despite his best efforts, it proved impractical on a tossing deck. Among those who tried to find a better way were Giovanni Domenico Cassini, Christiaan Huygens, and England's first Astronomer Royal, John Flamsteed; books and prints reflecting their work are also on display.

Nowadays, ships, planes, and even cars navigate with the help of satellites, and travelers (almost) always know exactly where they are. Life is safer and easier—but our curiosity about the world around us is as strong as ever. —*BE* E&S

Barbara Ellis is a writer and researcher for On the Map*, which is curated by Shelley Erwin, head of Archives and Special Collections. The majority of the books, prints, and artifacts on display were collected and later donated to Caltech by Earnest C. Watson, founder of the Watson Lecture Series and professor of physics and dean of the faculty at Caltech for many years. The* Tabulae Rudolphinae *are from the Rocco Collection, purchased by trustee Harry Bauer for Caltech in 1955.*

A rare and unusual map of the world designed by Kepler for his 1627 book of star tables, the *Tabulae Rudolphinae*.

Right: Using the "Brainbow" technique, in which neurons are labeled with differently colored fluorescent proteins, the researchers can map out neural circuits in zebrafish larvae. Because the larvae have relatively few neurons and are transparent, they make for a good model organism for studying the neural and genetic systems that regulate sleep.



WHY DO WE SLEEP?

While we can more or less abstain from some basic biological urges—for food, drink, and sex—we can't do the same for sleep. At some point, no matter how much espresso we drink, we just crash. And every animal that's been studied, from the fruit fly to the frog, also exhibits some sort of sleep-like behavior. (Paul Sternberg, Morgan Professor of Biology, was one of the first to show that even a millimeter-long worm called a nematode falls into some sort of somnolent state.) But why do we—and the rest of the animal kingdom—sleep in the first place?

"We spend so much of our time sleeping that it must be doing something important," says David Prober, assistant professor of biology and an expert on how genes and neurons regulate sleep. Yes, we snooze in order to rest and recuperate, but what that means at the molecular, genetic, or even cellular level remains a mystery. "Saying that we sleep because we're tired is like saying we eat because we're hungry," Prober says. "That doesn't explain why it's better to eat some foods rather than others and what those different kinds of foods do for us."

No one knows exactly why we slumber, Prober says, but there are four main hypotheses. The first is that sleeping allows the body to repair cells damaged by metabolic byproducts called free radicals. The production of these highly reactive substances increases during the day, when metabolism is faster. Indeed, scientists have found that the expression of genes involved in fixing cells gets kicked up a notch during sleep. This hypothesis is consistent with the fact that smaller animals, which tend to have higher metabolic rates (and therefore produce more free radicals), tend to sleep more. For example, some mice sleep for 20 hours a day, while giraffes and elephants only need two- to three-hour power naps.

Another idea is that sleep helps replenish fuel, which is burned while awake. One possible fuel is ATP, the all-purpose energy-carrying molecule, which creates an end product called adenosine when burned. So when ATP is low, adenosine is high, which tells the body that it's time to sleep. While a postdoc at Harvard, Prober helped lead some experiments in which zebrafish were given drugs that prevented adenosine from latching onto receptor molecules, causing the fish to sleep less. But when given drugs with the opposite effect, they slept more. He has since expanded on these studies at Caltech.

Sleep might also be a time for your brain to do a little housekeeping. As you learn and absorb information throughout the day, you're constantly generating new synapses, the junctions between neurons through which brain signals travel. But your skull has limited space, so bedtime might be when superfluous synapses are cleaned out.

And finally, during your daily slumber, your brain might be replaying the events of the day, reinforcing memory and learning. Thanos Siapas, associate professor of computation and neural systems, is one of several scientists who have done experiments that suggest this explanation for sleep. He and his colleagues looked at the brain activity of rats while the rodents ran through a maze and then again while they slept. The patterns were similar, suggesting the rats were reliving their day while asleep.

Of course, the real reason for sleep could be any combination of these four ideas, Prober says. Or perhaps only one of these hypotheses might have been true in the evolutionary past, but as organisms evolved, they developed additional uses for sleep.

Researchers in Prober's lab look for the genetic and neural systems that affect zebrafish sleeping patterns by tweaking their genes and watching them doze off. An overhead camera records hundreds of tiny zebrafish larvae as they swim in an array of shallow square dishes. A computer automatically determines whether the fish are awake or not based on whether they're moving or still, and whether they respond to various stimuli. Prober has identified about 500 drugs that affect their sleeping patterns, and now his lab is searching for the relevant genetic pathways. By studying the fish, the researchers hope to better understand sleep in more complex organisms like humans. "Even if we find only a few new genes, that'll really open up the field," he says. The future is promising, he adds, and for that, it'll be well worth staying awake. —*MW* e&s

The pair of colliding galaxies known as the Antennae, as seen by (from left to right) today's visible, infrared, and submillimeter telescopes. CCAT will see the dust-shrouded star-forming regions that the CSO sees, but with Spitzer's spatial resolution.

THE MKIDS ARE ALRIGHT

"Build CCAT!" the decadal survey says. That's the U.S. National Research Council's sixth decadal survey for astrophysics and astronomy, released in August. These surveys predict the greatest scientific opportunities and rank proposed research projects accordingly. The outlined projects offer the best prospects "for making discoveries—both anticipated and unanticipated—for which the next decade will be remembered." CCAT—a telescope initiated by Caltech, JPL, and Cornell that is slated for construction in the high-altitude Atacama Desert in northern Chile—was listed as a top priority for its part in the search for the first stars, galaxies, and black holes.

"The first two billion years of the universe will open up in the next decade," predicts Chuck Steidel (PhD '90), Caltech's DuBridge Professor of Astronomy. "CCAT has a starring role: it is the only telescope that can survey the dustiest and most luminous galaxies in the primordial universe. We expect some big surprises."

Astronomers have wanted a telescope like CCAT since the 1980s, when the Caltech Submillimeter Observatory (CSO) began to reveal dust clouds packed with embryonic stars in nearby galaxies. These clouds look dim or black to optical telescopes, but they blaze in the submillimeter- and millimeter-wavelength light that the CSO and CCAT are designed to see. This light falls between radio waves on the one side and near-infrared and visible light on the other. To see well at these wavelengths—just out of the reach of radio and optical telescopes—completely new cameras and spectrometers had to be developed.

This light may be tough to work with, but it holds the key to understanding galaxy formation. If star-forming regions are thick with dust, primeval galaxies may also be hidden by the dust and gas of their own formation. CCAT will survey huge swaths of sky at great depths, essentially looking back in time by catching photons that have been traveling for more than 10 billion years. Its superb site and 25-meter dish—more than twice as large as the CSO's—are big factors in its observing power. But the real revolution is down in the bowels of the telescope.

It has taken three decades of dogged work, false leads, and lucky breaks to develop the technology for CCAT's wideband spectrometer and its large-format cameras. *E&S* discussed this journey of a thousand steps with Jonas Zmuidzinas (BS '81)—the Kingsley Professor of Physics, Caltech's project scientist for CCAT, and a leader in detector development.

"So far, we have gotten just a small taste of what there is to learn at submillimeter wavelengths," says Zmuidzinas. Studying a submillimeter-bright galaxy often requires three telescopes. You need a submillimeter telescope to find the object, a radio telescope to pinpoint its location, and an optical spectrometer to analyze its chemistry and measure its redshift, which determines its place on the cosmic time-line.

CCAT will be able to do all of these things. Its spectrometer, the next generation of an instrument called Z-Spec, will have unprecedented bandwidth and be able to target multiple objects simultaneously. It will routinely find redshifts for distant, dust-obscured galaxies rich with new stars. Its cameras, using microwave kinetic inductance detectors (MKIDs), are expected to bring the state of the art from a few thousand pixels to many tens of thousands of pixels and beyond. They will capture detailed panoramas of the submillimeter sky.

Caltech and JPL were central to development of the new detectors. That's not because of one or two people—quite the opposite. In this small community, ideas fly from undergraduates to senior researchers to trustees to alumni (don't try to keep track of all the characters that follow!). Here, a good idea can generate the nimble collaboration more typical of a pro sports team—each player, aware of the skills and resources of the others, contributes what he or she can, whether it's a new method, a better production facility, a timely infusion of funding, or a novel design.

SIS OPENS THE SUBMILLIMETER

Our story begins in 1979, when Bell Labs' Tom Phillips—now Altair Professor of Physics at Caltech—invented the superconductor-insulator-superconductor, or SIS mixer. The SIS mixer was crucial to the development of radio-style receivers for the submillimeter band, and it is now used in nearly all submillimeter- and millimeter-wavelength telescopes. "It made sensitive high-resolution submillimeter spectroscopy and interferometry a possibility," says Zmuidzinas.

Jonas Zmuidzinas (BS '81), the Kingsley Professor of Physics and Caltech's project scientist for CCAT.

An SIS mixer channels photons to a tiny junction made of two layers of superconducting metals, each just a tenth of a micrometer thick, separated by a smear of insulation. Excited by the photons, electrons leap across the insulator by quantum tunneling, generating a measurable current with extremely low noise. John Tucker (BS '66) developed the theory behind these mixers, predicting that their noise levels could be reduced to the fundamental limits set by quantum mechanics.

Phillips, who had been a visiting associate at Caltech, joined the faculty that year. Once installed in Caltech telescopes, his prototype SIS receivers demonstrated fantastic potential, convincing JPL to dedicate researchers and lab space to the project. The CSO also sped ahead—its SIS receivers caught their first photons in 1987. JPL opened its Microdevices Laboratory in 1988, and the new facility turned physicists' heads nationwide.

One of those physicists was Zmuidzinas, then a postdoc in Illinois. He was designing ways to force-feed photons to an SIS junction with minimal losses. He had refined a device called a twin-slot mixer, in which two antennas collect light and guide it into microstrips made with superconducting metals.

Zmuidzinas returned to Pasadena in 1990. "Caltech was irresistible. The CSO had recently been completed. The Microdevices Lab had just opened, so there was a beautiful facility for doing this work." Today, descendents of the twin-slot are used in the Herschel Space Observatory's spectrometers and in the CSO's high-frequency instruments.

SPIDERWEBS AND SIN

A few years later, Zmuidzinas focused on the problem of finding distant submillimeter-bright galaxies, which would require a camera with at least a hundred detectors—one per pixel. At the time, the workhorse detectors were germanium bolometers. Bolometers, which are used in both cameras and spectrometers, absorb incoming photons and convert their energy to heat, which an electrical thermometer then converts to a measurable electrical signal. But the devices were laboriously assembled by hand. Zmuidzinas wanted to solve the problem by combining his twin-slot antennas with a new bolometer based on superconductor-insulator-normal (SIN) junctions that had just been invented by a UC Berkeley student. With this approach, the entire detector array could be produced by lithography—no hand-assembly needed!

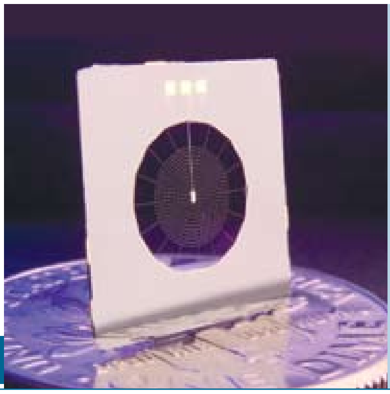
At that time, the late Andrew Lange, then a professor at Berkeley, and his student Jamie Bock were developing the spiderweb bolometer, a refined germanium bolometer in which everything could be mass-produced except the thermometer. The web, less than half the diameter of a dime, was photolithographed, gold-coated silicon nitride. The spider—the thermometer—was hand-placed in the middle. When the silicon backing material was etched away, the spider and web hung in free space, suspended on thin guy lines. Lange began a sabbatical at Caltech in 1994; when he decided to stay, Bock joined JPL as a postdoc. JPL's Microdevices Laboratory was just what they needed: "They had prototyped the device at Berkeley, but they needed good facilities to make a go of it," says Zmuidzinas.

Lange, Bock, and Zmuidzinas started down both paths—spiderwebs and SIN—but soon focused on the spiderwebs. They were more of a known quantity, and Lange and Bock wanted to create a working instrument quickly for upcoming experiments. Spiderweb bolometers made cameras faster and more accurate—they had more detectors and needed fewer photons to produce a measurable signal, and cosmic rays and the heat and shaking of nearby equipment affected them less. The 1998 BOOMERanG experiment, co-led by Lange, used them to provide the first experimental evidence that the universe is flat and that the "inflationary theory" is correct (see "An Ultrasound Portrait of the Embryonic Universe," in *E&S* 2000, No. 3). Similar bolometers are flying on the Herschel and Planck observatories—326 on Herschel and 52 on Planck. They were also used in a 144-pixel camera installed on the CSO in 2002.

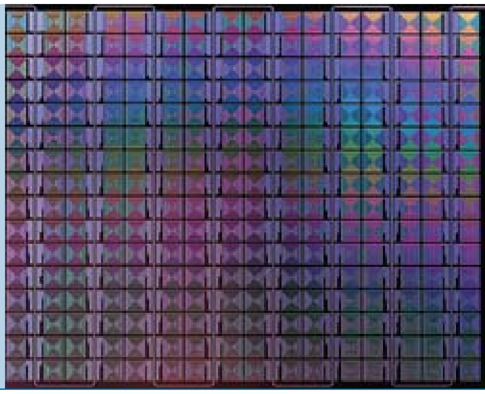
THE MISSING REDSHIFTS

In 1998, a UK team at the James Clerk Maxwell Telescope—located on the summit of Hawaii's Mauna Kea, just a few hundred yards from the CSO—announced that they had found distant submillimeter-bright galaxies. They had used hand-assembled, thread-suspended, pre-spiderweb bolometers. "It was a brute-force, inelegant solution, but they got there first," Zmuidzinas says.

The galaxies proved to be very faint and difficult to study at other wavelengths. In particular, their redshifts—usually measured with optical spectroscopy—remained largely unknown.



Left: A spiderweb bolometer sits on a dime. Right: Titanium nitride Microwave Kinetic Inductance Detectors, or MKIDs, of the type under development for CCAT's camera. The active area (pictured) is about a centimeter across, or roughly the size of the chip in which the spiderweb bolometer is suspended, but this MKID has a 16 × 16 pixel array instead of a bolometer's single sensor.



Zmuidzinas started to think about how to make a submillimeter spectrometer with enough bandwidth to measure redshifts for distant galaxies.

In an optical spectrometer, a grating diffracts incoming light, bouncing it to an array of detectors. The longer the light fans out before it hits the detectors, the more the resolution improves—but the instrument also gets larger. This becomes a serious problem in the submillimeter band, because the wavelengths are about a thousand times longer than in the optical. Hoping to shrink the instrument back down, Zmuidzinas considered confining the light in superconducting circuitry on a silicon wafer, similar to an ordinary printed circuit board. This would address the problem—the metal circuitry would confine the light vertically and also slow it down, reducing the required path lengths considerably. But experiments initiated by undergraduate Chiyan Luo (BS '00) showed that the circuitry would lose too many photons.

Meanwhile, Jamie Bock, by then a JPL research scientist, was also trying to make a better submillimeter spectrometer. He was looking into instruments that bounced light the old-fashioned way, with mirrors and lenses. But they were proving to be unmanageably large, so Zmuidzinas suggested a compromise using a machined-metal version of the superconducting spectrometer.

In 2000, Bock and Zmuidzinas joined forces to develop a new instrument that would draw on each of their approaches, and they were soon joined by Millikan Postdoctoral Fellow Matt Bradford, graduate student Bret Naylor (PhD '08), Hien Nguyen at JPL, and collaborators at other universities.

In Z-Spec, the resulting spectrometer that was first installed on the CSO in 2005, feedhorns funnel light into the 2.5-millimeter gap between two parallel metal plates, each more than a foot on a side. The light hits a faceted, arc-shaped grating, splintering off to be caught by 160 bolometers—variations on the spiderweb concept.

Z-Spec's bandwidth—on par with that of optical spectrometers—is over ten times larger than that of previous submillimeter spectrometers. The instrument recently measured redshifts of several distant, dust-obscured star-forming galaxies discovered with Herschel.

OF SQUIDS AND MKIDS

The story doesn't end with the smashing success of the spiderweb bolometers and Z-Spec. In fact, Lange and Bock's progress on the bolometers had left one box unchecked: "We didn't fulfill the vision of producing large arrays of detectors purely by lithography," Zmuidzinas says. It's a frequent quandary—do you spend more time on a new tool that can scale up, or do you prioritize the ability to do interesting science right away? The spiderwebs had mostly solved the issue of hand-assembly, but placing the thermometers and installing the wiring was still delicate and labor-intensive. In the late '90s, Zmuidzinas returned to the challenge of making a camera with simple wiring and thousands of mass-producible detectors.

Kent Irwin (BS '88) had made progress on this problem, in the meantime, when he found a simple, practical way to make use of superconducting bolometers as a Stanford graduate student in 1995. Called transition edge sensors, his bolometers used strips of superconducting metal films as thermometers. Small temperature changes in the strips reliably yielded measurable changes in resistance, once Irwin drew on the design of stereo amplifiers to keep the strips within a working temperature range. Then, in 1999, in his first job, Irwin and collaborators (including Erich Grossman, PhD '88) developed readout multiplexers using superconducting quantum interference devices (SQUIDs) that simplified the wiring for large bolometer arrays. Arrays of these detectors, incorporating novel antennas inspired by Zmuidzinas's work, are being developed at JPL for studying the cosmic microwave background and for sensitive spectroscopy from space.

It was a breakthrough, but the SQUID multiplexers seemed complicated to Zmuidzinas. The SQUID approach works well for certain applications, but it wouldn't scale up to the large detector count needed for CCAT's cameras. He and JPL's Rick LeDuc discussed the problem at a coffee shop near campus. LeDuc wondered: "Can't we use kinetic inductance somehow?"

This was a lightning bolt for Zmuidzinas. Back in his office, he scanned the literature. Photons absorbed by a superconductor would produce quasiparticles. A quasiparticle population boom would change the superconductor's inductance, which would change the circuit's resonant frequency. Perhaps he and LeDuc could design a lithographed superconducting resonator and use its frequency change as the detect-

If the human eye could see submillimeter light, this is how the skies over the CCAT telescope would look. CCAT will be built atop Cerro Chajnantor in Chile's Atacama desert—at an elevation of 5,612 meters, one of the highest and driest places on Earth. This is essential, as water vapor absorbs submillimeter waves.

able response. Each resonance would be sharp, occupying a narrow range of frequencies. You could tack resonators next to each other on one readout wire, maybe into the thousands. There was no theoretical ceiling for the quality of each resonator.

RESONANT INTERACTIONS

Zmuidzinas and LeDuc shared the idea with Tom Tombrello, Caltech's Kenan Professor and then chair of the Division of Physics, Mathematics and Astronomy. Tombrello spoke with then provost Steve Koonin, who connected him with trustee Alex Lidow (BS '75)—who provided substantial seed funding. "Lidow's gift came at a critical time for us—it allowed us to get the equipment we needed and get set up to do this in the right way," Zmuidzinas says. Prominent researchers from Caltech and JPL, as well as other universities, signed on to the effort. Koonin and Tombrello also talked with JPL's Jakob van Zyl (PhD '86), who helped move the project ahead.

JPL's Peter Day (PhD '93) suggested making the resonators using a structure called a coplanar waveguide, etched from a superconducting metal film deposited on a silicon wafer. In the resulting resonators, the distance covered by the microwaves as they bounced back and forth totaled more than a kilometer!

"They were getting *Q*'s (a quality factor related to path length) of a million-plus," says Keith Schwab, an applied physicist at Caltech. "People in quantum computing and applied physics couldn't believe it. It's had a big impact on our work. And the technology is easy to implement."

Beyond their unanticipated benefits, the new MKID circuits actually *work*. The team has created a camera with 2,304 detectors—it will be installed on the CSO in the fall of 2011. In development are new versions of MKIDs, in which the radiation is absorbed in meandering superconducting strips that also let energy slosh back and forth between inductors and capacitors. They will have *Q*'s in the tens of millions. These MKIDs rely on superconducting titanium-nitride films, a choice suggested by LeDuc. They are very simple, dropping costs and enabling fabrication of extremely large cameras for CCAT.

The invention is also inspiring new applications: Caltech physicist Sunil Golwala is exploring ways to use titanium-nitride MKIDs to detect dark matter, Ben Mazin (PhD '04) is developing optical-wavelength versions for astrophysics, and Zmuidzinas and Day hope to use the material to make a nearly ideal microwave amplifier. These ongoing efforts are supported by the Keck Institute for Space Studies and by the Gordon and Betty Moore Foundation, which also enabled earlier detector work.

"As you can see, you bounce around and it takes a while to land on the right idea," says Zmuidzinas. The instruments at the heart of CCAT will bring decades of work to fruition. Looking back, Zmuidzinas reflects, "There are always such surprising connections. Who would have thought that trying to look for submillimeter galaxies would spark an idea useful in quantum computing? But that's how research works. There are deep, hidden connections among fields. We all learn from each other."

—*AW* E&S

Left: Looking like a knight in a chain-mail hood, Koch dons an array of electroencephalography (EEG) electrodes for a brain-function test.
Right: Afterward, he appears to have been attacked by a giant squid, thanks to the array's suction cups.

Be Aware of Your Inner Zombie

By Andrew Porterfield

Zombies walk among us. In fact, we couldn't get along without them—operating below the threshold of awareness, zombie systems in our brains take care of all sorts of routine tasks without any conscious effort on our part. Studying such unconscious processes is beginning to throw light on how the conscious mind works.

In the 1968 horror classic *Night of the Living Dead*, terrified people trapped in a Pennsylvania farmhouse try to survive zombies hungry for human flesh.

But real zombies aren't like that, according to neurobiologist Christof Koch. "The word 'zombie' is a surprisingly technical term, developed in detail by philosopher David Chalmers. Zombies are exactly like you and me except that they have no feeling or awareness," Koch says—a rather more sympathetic view than director George Romero's. Chalmers's 1996 book, *The Conscious Mind*, proposed these zombies as a "thought experiment" through which we could explore the question of whether a creature could exist that displayed the full range of human behavior but lacked conscious sensations. Such a zombie would get up, get dressed, and go to work like you and me. If you asked it over lunch what its favorite band was, it might answer, "Pink Floyd," and perhaps even invite you on a date to see a local tribute band cover *Dark Side of the Moon* on Saturday. But the zombie would not be experiencing the taste of the sandwich it was eating, nor would it "enjoy" the music as a human would. Do any natural laws prohibit the existence of such beings? Chalmers asked.

In fact, it's the unconscious, or "zombie," systems in our brains that help us get through daily life, Koch says, and they can show us how consciousness really works.

Koch has been fascinated by the phenomenon of consciousness for more than two decades, but his interest started not with a penchant for horror cinema, but with a toothache. "I was teaching a course at the Marine Biological Laboratory in Woods Hole, Massachusetts. So I was lying in bed, had this terrible toothache, I'm taking aspirin but it's still persistent." He began to ask himself, "Why should that hurt? Where does the feeling come from?"

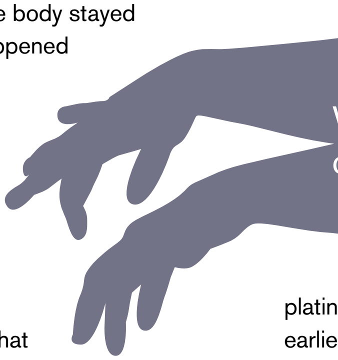
Koch blends techniques from psychology,

biology, and neurology to attack the fundamental questions of consciousness: “What is it in the brain that enables us to feel? What part of the human and animal brain is necessary to be conscious? And how does consciousness arise out of matter?”

The debate about whether there’s an actual place for consciousness in the brain goes back millennia. Plato and Aristotle held that the mind was entirely divorced from the physical body—like parallel Las Vegases, what happened in the body stayed in the body; what happened in the mind stayed in the mind. More recently, the French philosopher René Descartes argued that the mind and the brain could influence each other. He proposed that the soul resided in the pineal gland—a solitary lump in the shape of a pine cone (but about the size of a grain of rice) that lies almost exactly in the middle of the brain, surrounded by the matched pairs of structures that make up the rest of the brain. This gland’s singular nature and central location, he argued, clearly marked it as something special, and what could be more special than the physical seat of what makes us human? (Alas, we now know that the pineal gland doesn’t do much more than help control our cycle of waking and sleeping by secreting the hormone melatonin in response to darkness.)

A RISKY BUSINESS

When Koch entered the field in 1988, the study of consciousness was not considered serious science. A mountain climber and trail runner, he describes himself as a risk taker. “Even without tenure, I was adventuresome, and I was very interested in consciousness. But talking about consciousness was a sign that you were retired, or had a Nobel Prize, or were a mystic and slept next to crystal pyramids,” he laughs. “It was like talking about sex during Victorian times—it was just taboo.” Koch paired up with the vigorously *un*retired Nobel laureate Francis Crick, the codiscoverer of the double-helical structure of DNA, the molecule of heredity, who had moved from probing the workings of genes to contemplating the workings of the brain 15 years earlier. The two remained close collaborators until Crick’s death in 2004.



> When Koch entered the field in 1988, the study of consciousness was not considered serious science.

“Francis had thought for a long time about consciousness, and in his view it was a scandalous state of affairs that people were studying the brain without ever referring to the fact that this brain produces consciousness every day, day in and day out,” Koch recalls. Together, the duo published about two dozen papers; Crick also wrote the foreword to Koch’s 2004 book, *The Quest for Consciousness*, which introduced the notion of zombie agents to the unsuspecting world beyond the neurobiology community.

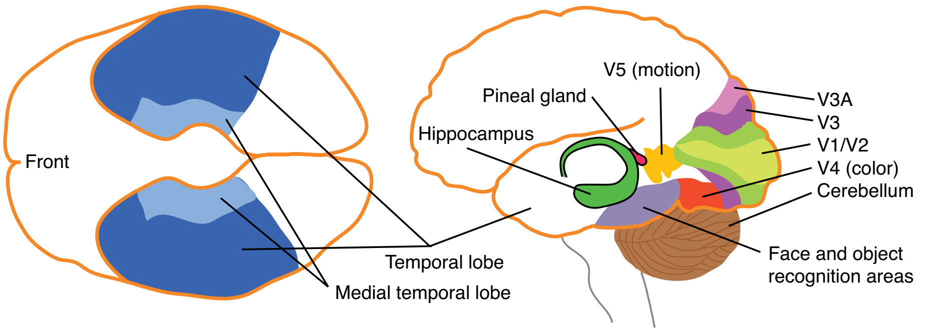
Today, many laboratories study consciousness, and Descartes’s intellectual descendants are still asking: Where in the brain is the mind? Consider a computer, Koch says. “If you rig a thermometer to a computer and put them both next to a heat source, the thermometer will transmit the ambient temperature to the computer. Once the temperature rises above some threshold, the computer can be set to print out a message. ‘It is too hot. I’m in pain.’ But does the computer actually experience pain? I don’t think so. At this point, its response is nothing but a programmed instruction, a reflex. At a certain threshold temperature value, some electrons flow onto a gate, a transistor opens another gate, opens the register, records the content, and prints out a statement. There is no feeling involved.”

Now compare that to the sensation of someone stomping on your toe. Again, a train of electrical impulses—this time mediated by calcium, sodium, potassium, and other ions—flows from your foot to your brain. “I can say this is just biophysics—signals moving about inside the nervous system. There’s no pain feeling anywhere. But without any doubt you’ll feel this bad thing, pain. So how is it that a physical system like a brain can produce a subjective state, but another physical system, the computer, doesn’t? This is the heart of the mind-body problem.”

Some headway has been made since the days of Descartes, and scientists have discovered that not all of the brain is involved in creating consciousness. The cerebellum, for example, controls the timing of motor movements, and it contains half of the brain’s neurons. If you lose your cerebellar function, you will be unable to coordinate your muscle movements, a condition called ataxia. You might stagger and sway while you walk, for instance. “You won’t be in a rock band, you won’t be a ballerina or a climber, but your visual consciousness will be marginally impacted, if at all,” Koch notes.

In Koch’s world, the zombies are in our brains. In the pop-culture world, the zombies are out for our brains.

Nudist Colony of the Dead, © 1991 Pirromount Pictures.



Left: The regions mentioned in this article lie deep within your brain. (The brain's outer surface is outlined in orange.) Visual processing begins in area V1, also known as the primary visual cortex. V2 through V5 do additional analysis before sending the information on to the medial temporal lobe, the hippocampus, and other areas where consciousness may lurk. V1 through V5 are on the inner, facing surfaces of the cerebral hemispheres; the hippocampus, the cerebellum, and the pineal gland straddle the brain's midline. Far left: A horizontal slice through the temporal lobes.

I SEE, THEREFORE I AM

Koch attacks the problem of consciousness through the brain's visual system. He originally established his laboratory—not coincidentally, painted in bright primary colors—to study visual perception, trying to understand how we focus on one aspect of a scene, and to figure out how this form of selective visual attention could be taught to machine-vision systems. This background lent itself easily to experiments with visual consciousness.

Koch's other longtime collaborator, Itzhak Fried, is a professor of neurosurgery at UCLA who implants microelectrodes into epilepsy patients whose seizures cannot be controlled by nonsurgical means. Fried uses these electrodes to find the abnormal brain-cell activity caused by epilepsy; the electrodes pinpoint the lesions' locations in order to guide his scalpel. The electrodes—as many as a dozen per patient, with each one sprouting as many as nine microwire probes from its tip—show up nicely in CAT scans, which provide their tips' three-dimensional coordinates to within a few millimeters.

Even better, from Koch's point of view, each microwire is sensitive enough to pick up the musings of a single neuron. As luck would have it, some of the deep-brain centers involved in recognizing and remembering people are in brain areas that are most often affected by epilepsy, such as the hippocampus. Thus Fried's electrodes give Koch a window into—or, more accurately, a water glass pressed up against the wall of—those regions of the brain.

The electrodes remain in the patients' heads for up to two weeks. That's a long time to spend hanging around in a hospital, so the simple video games that Koch and his colleagues have designed for their experiments offer a welcome distraction.

As the patients stare at the computer screens, the researchers use the electrodes to look for neural correlates of consciousness, or NCCs, which Koch and Crick had defined in a 2003 paper called "A Framework for Consciousness." The paper proposed that visual NCCs are small coalitions of nerve cells that collect information from the back of the cerebral cortex, where the preliminary processing of visual information is performed, and establish sets of two-way communication links with other parts of the cerebral cortex at the front of the brain.

The receiving regions include the medial temporal lobe, where Koch, his grad student Gabriel Kreiman (MS, PhD '02), and Fried had already found neurons that only fired when a person was consciously perceiving an image. That discovery had been made by fitting Fried's patients with special LCD glasses that were, in effect, separate TV screens for each eye. A picture would appear on one screen and remain there so that the test subjects could clearly see it. Then a second, different picture would be momentarily flashed into the other eye—a technique known as "flash suppression," because the new picture in the second eye would suppress the perception of the old image in the first eye. In other words, the fresh image wiped the older one from consciousness, even though both were still there to be seen. The neurons' firing rates reflected this. Kreiman noticed that, in most cases, each neuron being recorded would respond to only one specific image, say a picture of a smiling girl. When the image was flash-suppressed, however, the neuron became far less active, even though its preferred picture was still displayed. Those neurons, therefore, followed whatever was in the patient's conscious perception. They fired when the patient saw the image, and they didn't fire when the patient didn't. Wherever the brain's representations of the suppressed images—visible, but not consciously seen—might reside, they had to be somewhere else.

SEEING JENNIFER ANISTON

That some neurons fired only in response to specific pictures was no big surprise—after all, pattern recognition is one of the things our brains do best. But in 2005, postdoc Rodrigo Quian Quiroga; grad student Leila Reddy (PhD '05); Kreiman, by then at MIT; Koch; and Fried announced the discovery of individual neurons in the medial temporal lobes that recognized specific *people*. It didn't matter whether the picture presented was full-face or in profile, or even a line drawing or a caricature; the neuron "knew" who it was looking at.

"The first neuron we found behaving this way was a Bill Clinton neuron back in 2002," Koch recalls. "Then, there was a second neuron that responded to three different cartoon images of characters from *The Simpsons*, and a third selective neuron to basketball superstar Michael Jordan. When we first submitted the paper to *Nature*, the referees didn't believe this unheard-of

Your brain wires up groups of cells that respond to things we constantly encounter. “I had no idea who Jennifer Aniston was before we did these experiments, but presumably I now have a set of neurons that respond to Jennifer Aniston,” Koch chuckles.

degree of selectivity, since we only had three such neurons. Three neurons don’t make a discovery. So we went back and characterized many more of these remarkable cells—51 in that 2005 *Nature* paper, and more since then.”

Grad student Stephen Waydo (PhD ’08), on loan from control and dynamical systems professor Richard Murray (BS ’85), and Koch pieced together an explanation for the process behind such extreme selectivity. Although the world around us presents an infinite variety of stimuli, Waydo and Koch assumed that most of the patterns that come to us through our senses are due to a small number of causes. “For instance, when I’m at home, most of the visual activity in my brain at any given moment is caused by me seeing my family and the furniture in the rooms around me, all of which are very familiar to me,” Koch says. Working from this premise, Waydo devised a set of machine-learning rules that would enable a computer to identify such commonly occurring patterns—discovering for itself the Platonic form, if you will, of Koch’s sofa—and then represent each one as a specific pattern of outputs from a collection of “neurons.”

Similarly, says Koch, “Your brain wires up groups of cells, what we call concept cells, that fire specifically in response to things we constantly encounter.” To illustrate this, he brings up on his computer a session with one of Fried’s patients. An image of Marilyn Monroe appears on the screen: a rapid-fire *trrrppp*, *trrrppp*, *trrrppp* pours from the speakers. Then, actor Josh Brolin; nothing.

“I had no idea who Jennifer Aniston was before we did these experiments, but presumably I now have a set of neurons that respond to Jennifer Aniston,” Koch chuckles. “It’s an efficient way of dealing with the world. It allows infants to learn early the lessons that stay with us: first you learn to recognize your parents and your siblings in this abstract and invariant matter, and your dog, and all the other important people, animals, and things that your brain constantly encounters. Then when you get older, it’s on to mastering more abstract things, like Marcel Proust or $e = mc^2$.”

Concept cells respond to sensory stimuli of all kinds—in Aniston’s case, for example, not just seeing her, but hearing the sound of her voice or even reading her name; this set of neurons will activate when exposed to any aspect of the Zen of Jen.

There are two schools of thought about how concept cells work. The distributed-population hypothesis invokes a large number of neurons, each contributing a little bit to encoding the percept. The power of this approach lies in the great number of distinct objects that can be encoded, and in the robustness of their representation—lose any one neuron, and the percept hardly changes. The sparse-coding hypothesis, on the other hand, proposes that a small network of neurons is entirely responsible for the encoding. The ultimate sparse network would be one consisting of a single cell; this reduction to the extreme is known in the trade as the “grandmother cell” hypothesis, because it implies that somewhere in your brain there lives a cell whose sole duty is to recognize your grandmother.

At first blush, the existence of Jennifer Aniston neurons would seem to support the grandmother-cell hypothesis, but “there is something to both sides,” says Koch. In 2008, Quian Quiroga, Kreiman, Koch, and Fried found that yet another of Fried’s patients had a neuron in the hippocampus (an interior region of the medial temporal lobe) that responded not only to Aniston but to her *Friends* costar Lisa Kudrow. Since the two actresses have only one degree of separation on the small screen, it seems reasonable that their NCCs might share a few cells as well. (Another cell in the parahippocampal cortex of a different patient fired in response to both the Eiffel Tower and the Leaning Tower of Pisa but not to other landmarks, displaying a similar power of generalization.) So it appears that the networks are indeed sparse, but maybe not *that* sparse—they contain enough members to be both very selective and very abstract at the same time.

A couple of famous people who might be in your head.
The first “concept cell” that Koch’s team discovered fired in response to pictures of President Clinton.
If you’ve watched more than a few episodes of *Friends*, you’ve probably got a set of neurons that respond to actress Jennifer Aniston.
Once a network of concept cells has been wired up, it will be activated whenever it recognizes the object of its obsession. It doesn’t matter whether the image it sees is a grainy black-and-white photo or even a scrawled cariacture; nor does it matter if the subject is seen in a full-face view, in profile, or even partly obscured.
In fact, the stimulus doesn’t even have to be visual. Concept cells will react to sounds, smells, and even the written word—any sensory stimulus that we associate with that person.

LIVING THE ZOMBIE LIFE

So what do zombies have to do with any of this? More than we'd like to admit, apparently. In his upcoming book, *Consciousness—Confessions of a Romantic Reductionist*, Koch recalls a trail-running session in which he encountered a rattlesnake. "Something made me look down. My right leg instantly lengthened its stride, for my brain had detected a rattlesnake sunning itself on the stony path where I was about to put my foot," he writes. "Before I had seen the reptile or experienced any fear . . . I had already acted to avoid stepping on it." Had he been forced to think about consciously adjusting his stride, it would have been too late.

This unconscious, automatic response was choreographed by one of our zombie systems. While it's well known that the nervous system controls many body functions without conscious effort—things such as heartbeat, breathing, and digestion—Koch estimates that about 90 percent of our activities are the work of unconscious zombies.

"The central insight of Sigmund Freud is that you're not conscious of most of the stuff in your brain. For example, we spend much of the day typing. Now, if I ask someone, 'What finger do you type the letter *f* with?' most people won't know. They have to pantomime the movement to realize that it's the left index finger. But if you don't consciously think about it, your fingers will do the typing by themselves." Even activities as seemingly varied and unstructured as Koch's mountain-climbing adventures call on these zombie systems most of the time. Nearly all of his risky moves up the side of a cliff are so ingrained that he doesn't give them a thought.

"So why isn't all of life like that?" he asks. "Why not have a completely zombie existence?" Because life throws us curve balls, that's why. "The world is so complex; you have to do things that are nonroutine. Let's say there was an earthquake right now. You would look first at the glass window, which could shatter and seriously injure you, and then you would look around for a safe way to get outside. Reacting to an earthquake isn't something you've trained for hundreds of times." But for repetitive behaviors, even very elaborate ones, it's a convenient way for our brain to handle the situation with minimal effort.

PAYING ATTENTION

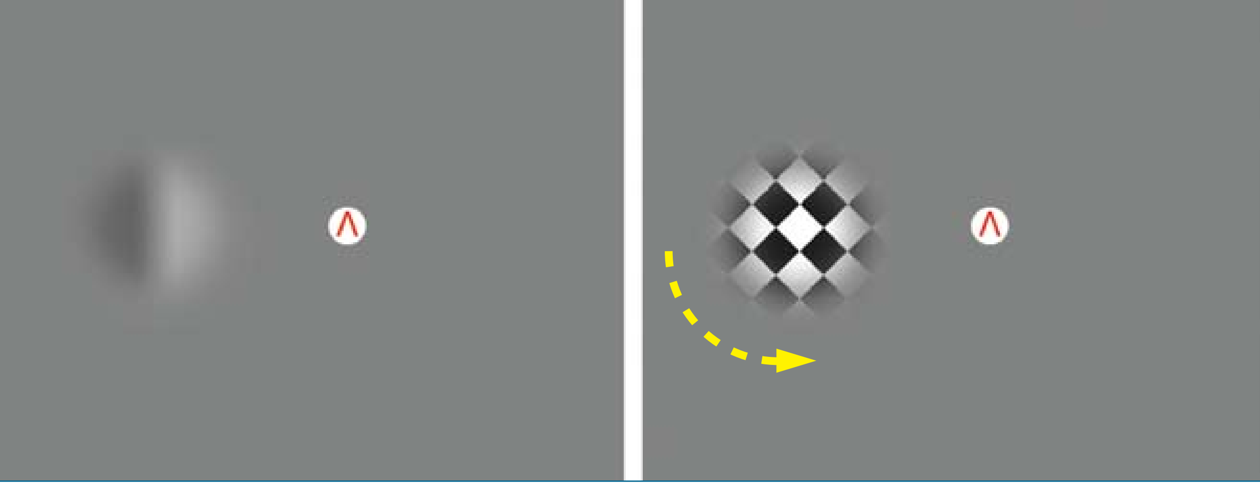
But even with an army of zombies at our command, "we suffer from information overload," says Koch. "We have to concentrate on the essentials; otherwise we wouldn't get anything done. Attention is the brain's way of maintaining focus." But attention is not the same as awareness or consciousness, he adds. While consciousness involves the general awareness of the world around us, or what we think is the world around us, attention is a spotlight. Attention takes hold of one aspect of our environment, whether it's scanning your DVD collection for the seventh season of *Friends* or listening to one person in a crowded room. It's a mechanism for selecting for further processing a few rivulets of information out of the flood that inundates our senses, providing the brain a way to organize multiple inputs and make sense of the world.

> Could the complexity of a system automatically create consciousness? Are we on the verge of a sentient Internet? Maybe, Koch says.

Scientists have long assumed that attention and consciousness are the same, or at the very least heavily intertwined. This past May, biology postdoc Jeroen van Boxtel, psychology and neuroscience postdoc Naotsugu Tsuchiya, and Koch demonstrated that this assumption is wrong. In these experiments, members of the campus community were asked to fixate their eyes, without any movement, on a dot in the center of a computer screen. Then, off to one side of one eye's field of view, a Gabor patch—a computer-generated blur resembling a small smudge—would appear for four seconds and then vanish, leaving an afterimage in the eye that had seen it. (Afterimages are the oldest tools of visual psychologists, as they are easy to induce and manipulate in reproducible ways.) The volunteers pressed a button when the afterimage disappeared.

At the same time, the participants were asked to count the number of times a specific symbol appeared among a series of symbols that rapidly flashed, one by one, at the center of their gaze. In some of the runs, the correct symbols were made deliberately hard to spot—a demanding task requiring full attention. In other runs, the task was easier, meaning that the volunteers could divide their attention between the Gabor patch and the stream of symbols, even as they continued to stare at the dot. Either way, the subjects were conscious of the patch, regardless of how much of their attention they could give it.

But here things got interesting. In a second set of experiments, the Gabor patch was removed from conscious perception by using the flash-masking technique: a



The two-eye test of consciousness. As the subject stared at the white disks, a Gabor patch would appear in one eye's field of view (far left). If a rotating checkerboard (left) was then flashed in the other eye to suppress the Gabor patch, the patch's afterimage was also affected.

second, high-contrast pattern that flickered and rotated was shown in the same relative location as the patch, but in the other eye's field of view. Now the subject could see only the moving pattern, not the stationary Gabor patch.

Not surprisingly, the afterimages lingered longer when the Gabor patch was consciously visible. One would also expect that the afterimages would be more persistent when attention was being paid to the patch, because of the mental effort devoted to processing that visual information. In fact, the opposite occurred. When the subjects had to pay full attention to the symbols at the center of their gaze and therefore couldn't concentrate on the patch out at the periphery, the patch's afterimage took *longer* to disappear—and this was true no matter whether the patch was masked or visible.

For the first time, consciousness and attention had been teased apart and shown to operate not only independently but in opposition to each other—a percept had been affected by whether or not it had been a focus of attention, regardless of whether the subject had been conscious of seeing it. This implies that somewhere in the brain, focused attention and consciousness—without attention—are somehow being handled differently. "The history of any scientific concept—energy, the atom, the gene, cancer, memory—is one of increased differentiation and sophistication until it can be explained in a quantitative and mechanistic manner at a lower, more elemental level," says Koch. "Making the distinction between attention and consciousness clears the decks for a concerted, neurobiological attack on the core problem of identifying what is necessary for consciousness to occur in the brain."

DESCARTES AND SOUL

Religion is rarely a popular topic in the laboratory, but anybody who studies consciousness can't escape the question: where, if anywhere, is the soul? Are we something more than a mosaic of cells, proteins, lipids, and DNA?

"It's a very old concept, and it means many things to many people. This is what Descartes, among others, was addressing," Koch says. "Consciousness is definitely the modern conception of the soul. But does that mean the soul resides in the brain?"

So, while Koch and his team are focused on finding the neural correlates of consciousness, and mapping the exact pathways that give rise to awareness, he's looking to what lies beyond. "It may be the complexity that matters. Consciousness is a property of complex entities and cannot be further reduced to the action of more elementary properties," he writes in *Consciousness*. Could the complexity of a system automatically create consciousness? Once a technological threshold has been crossed, could we re-create it? Are we on the verge of creating a sentient Internet? Or a robot that can feel?

Maybe, Koch says. If we can define consciousness well enough to pick out an NCC and say, "That's how we feel pain," we might be able to create a machine that "experiences" the same sensation. That done, we could download the electronic NCC onto a disk, and, as Koch cheekily proposed in a 2008 *IEEE Spectrum* article, auction it off on eBay. Talk about selling your soul. E&S

Christof Koch is the Troendle Professor of Cognitive and Behavioral Biology and professor of computation and neural systems (CNS). He studied physics and philosophy at the University of Tübingen in Baden-Württemberg, Germany, earning his MS in 1980 and a PhD in biophysics in 1982. He came to Caltech as an assistant professor in 1986 to join the just-established CNS program—the first of its kind in the world.

On November 18, Koch and Caltech biologist David Anderson were selected as two of the inaugural Allen Distinguished Investigators by the Paul G. Allen Family Foundation—a group of seven scientists "working on some of the most exciting research in biology and neurology," according to Microsoft cofounder Paul Allen. (For more on Anderson's work, see page 25.)

Koch's research has been funded by, among others, the National Institute of Mental Health, the National Science Foundation, the Defense Advanced Research Projects Agency, the Office of Naval Research, the Gordon and Betty Moore Foundation, the Swartz Foundation for Computational Neuroscience, the G. Harold & Leila Y. Mathers Charitable Foundation, and the Gimbel Fund.

This article was edited by Douglas L. Smith.

"Like It or Not, We Are Living on This Planet"

NASA's Aqua satellite captured this dramatic image of thick ash pouring from Iceland's Eyjafjallajökull Volcano on April 17, 2010. The plume reached heights of over nine kilometers and disrupted air traffic across Europe for weeks. Still, this eruption was demure compared to volcanic events that have occurred in Earth's past history.

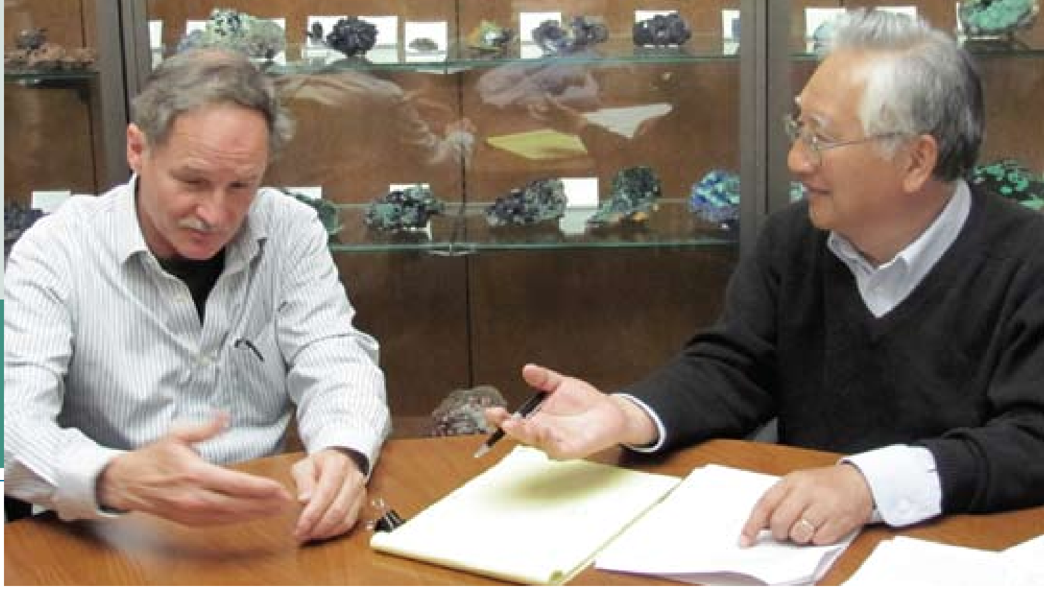
The number of large destructive earthquakes in this last year, plus a recent flurry of medium magnitude quakes in California, has led many people to ask, Are we in a period of heightened temblor activity, and is it likely to continue? It's also raised questions among both scientists and laypeople about whether these events are related—and if so, how. The eruption this past spring of an Icelandic volcano, which disrupted air traffic in Europe for weeks, serves as an additional reminder that we live on a volatile planet. What, if anything, does this apparent uptick in geological activity portend, and how does it compare to events in Earth's past history? E&S *sat down with Hiroo Kanamori, the Smits Professor of Geophysics, Emeritus, and Joe Kirschvink, the Van Wingen Professor of Geobiology, to hear their thoughts.*

Between February and September this year, earthquakes ranging from magnitude 6.8 to 8.8 have occurred in regions as far-flung as Sumatra, China, Chile, New Zealand, and Baja, California. Are we in fact seeing more large quakes than usual?

Hiroo Kanamori: There are a couple of ways to answer this question. If you look at very major earthquakes, we are not seeing as much activity as between 1950 and 1965, when there were three events of magnitude 9 or greater in which an enormous amount of energy was released.

However, if we total up the number of quakes over magnitude 8 that have occurred since the first great Sumatran quake of 2004, we do find that these numbers really have increased. On average about

Geobiologist Joe Kirschvink (BS '75, MS '75) and geophysicist Hiroo Kanamori get together in the room housing Caltech's gem and rare-mineral collection to talk about earthquakes, volcanoes, and other past perils of life on Planet Earth.



By Heidi Aspaturian

one quake per year is magnitude 8 or larger. Since 2004, on average we have had two quakes of that size or more annually.

Is this statistically significant?

HK: We don't really know! Thanks to a study that's been going on for about the last 18 years, we do know a great deal more than we used to about triggering events in earthquakes. We now know that every large earthquake sends out seismic waves that can travel some distance and potentially activate seismic activity elsewhere. We saw this in a particularly spectacular way during California's 1992 Landers quake in the Mojave Desert, where earthquake activity affected areas as far away as Yellowstone National Park. In 2002, the Denali earthquake in Alaska touched off seismic activity in California, a considerable distance away.

So, as we look at the increase in major quake activity over the last six years, it is theoretically possible that the seismic waves generated in 2004 by the magnitude 9.3 Sumatran quake acted as a trigger for at least some of these events in other parts of the world. But it has not been confirmed.

How well do scientists understand the physical mechanisms that might touch off a quake cascade like this?

HK: We have several different models and theories. The most straightforward mechanism would be one in which the seismic waves increase stress on other faults that they're passing through. If those faults are already close to rupture, this seismic impact may be enough to push things over the edge.

There are also cases in which this activity is delayed. This appears to be what happened this summer when the magnitude 7.2 quake that had occurred in Baja California in April touched off two moderate quakes in June and July on the San Jacinto fault in Southern California.

Do seismologists have an explanation for this delayed activity?

HK: Again, several theories or models have been proposed. One possible scenario is that these delayed quakes occur on faults where the stress level is just below what is required to produce an earthquake. Seismic waves reaching the fault from another quake are not sufficient to generate an event immediately, but because faults are essentially in constant, incremental motion, the seismic waves may be enough to increase that speed of motion to the point where the fault accelerates toward the breakage threshold and then, after a time, you have a quake. Every fault contains a large number of nuclei—or potential sources of rupture—that are in a sense at different levels of maturity. Some are farther from failure, some are closer, but as the fault itself is shaken, every one of these nuclei moves closer to failure. In these models, shaking those sources won't produce a quake instantly, but it will accelerate motion along the fault sufficiently to eventually tip one or more of them over the failure threshold. In other words, instead of failing instantaneously, the movement increases over time until a failure threshold is reached, and then there's a quake.

Does what seismologists now know about the triggering effect give them any added ability to predict where the next quakes are likely to occur?

HK: Well, for the triggering mechanism to work, you must first have a region that is ready to go. If a stress wave travels through a region where there is no stress accumulation, nothing is going to happen. So, we cannot make these kinds of predictions unless we know how close particular areas are to failure.

In the Baja case, as with many others, there's a good deal of research and debate going on. In general, when you are dealing with earthquakes, it continues to be very difficult to demonstrate which mechanism accounts for a specific event. And that is in large part because you are investigating unique events that happen over very large timescales. You can't go into the laboratory and replicate the quake that just occurred. The bottom line in earthquake science is that nature does not give up her secrets easily.

Really, the fundamental need is still to study particular fault zones or volcanoes to see what the current stress conditions are. That is precisely what many seismologists are investigating now. They are making in-depth studies of exactly how stress is building up, what the background activity is, and

"We now know that every large earthquake sends out seismic waves that can travel some distance and potentially activate seismic activity elsewhere."

> "The Icelandic eruption that we saw this spring was *tiny* compared to eruptions that have happened previously in Earth's history."

working to develop a more comprehensive picture of significant fault zones. Our technology, instrumentation, and field practices have improved quite a bit in the last decade, and we have been making good progress.

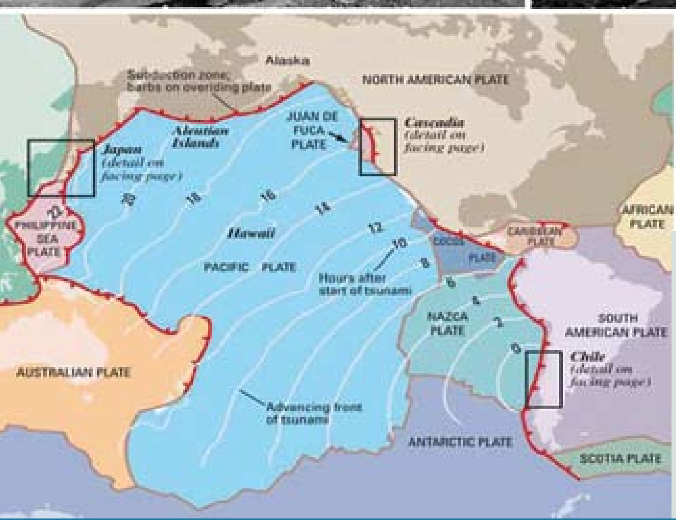
To give you one example, this year is the 50th anniversary of the biggest quake of the last century—the 1960 Chilean earthquake. Today we give it a magnitude of 9.5, but we still don't really understand how big it was. This was a huge event. It caused widespread death and damage in Chile and sent a tsunami that struck the island of Hawaii without warning and killed dozens of people. Contrast this to the latest large Chilean quake in February, which was a magnitude 8.8. Within one hour of that quake, the U.S. Geological Survey had amassed a great deal of relevant information and sent it out. Almost everything that followed—hazard mitigation, tsunami warnings, and so forth—was based on the rapid-response and early-warning systems that have been developed over the last several years.

So it's very clear that we can make a huge contribution to society by gaining a better understanding of the processes that underlie major quakes and then coming up with better tools for dealing with them. That's been very exciting for us.

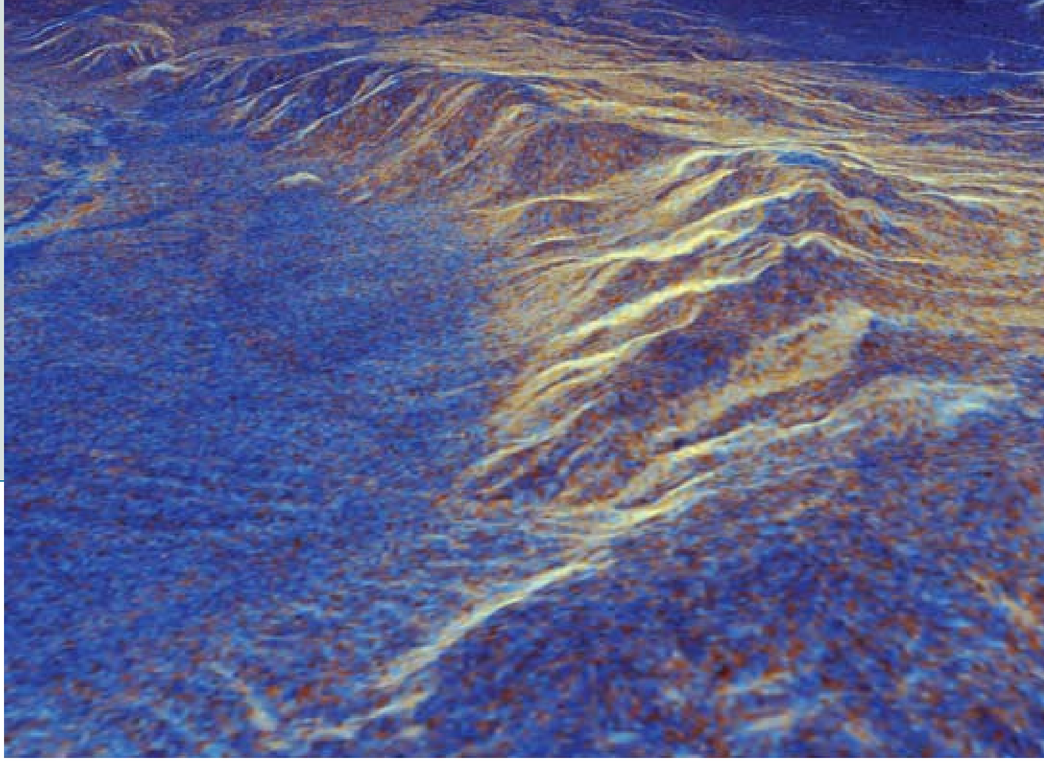
What do you each find most interesting about all this recent geologic activity?

Joe Kirschvink: I don't know if there's any relation between Iceland's volcanic eruption and this seismic activity. Most likely, it's just a coincidence. But the Iceland volcano was definitely one of these things that was on the verge of eruption. It had to have a major magma chamber underneath it that was ready to go. It's also interesting that the ash cloud that caused so much atmospheric havoc was partially due to the water that's being melted away from the glacier overlying the volcano. If that enormous volume of water had not been there, it wouldn't have been such a headache. Mixing water with hot, erupting magma leads to a particularly violent type of eruption. It's called a "phreatic explosion"—the root word's from the Greek, meaning "well"—and it is particularly good at producing fine-grained volcanic ash that can be carried long distances. So the troubles we saw were basically just a result of having a volcano at high latitudes under a substantial ice sheet.

HK: I think that what we need to realize is that this type of activity has gone on for a long time, and it will continue to go on. Basically, whether you like it or not, we are living on this planet. And it can be a perilous place.



Clockwise, from upper left: (1) The devastation wrought by the Great Chilean Quake of 1960, whose estimated magnitude of 9.5 ranks it as the largest temblor of the 20th century. (2) Residents of Hilo, Hawaii, survey the damage after a tsunami touched off by the quake struck the Big Island with little advance warning. (3) Several hours later, the tsunami flooded coastal regions of Japan, forcing residents to flee to higher ground. (4) A U.S. Geological Survey map traces the tsunami's path across the Pacific from a subduction zone along the coast of Chile. Its waves reached Hawaii in 15 hours and Japan in 22.



Three quarters of a billion years ago, massive eruptions of eastern California's Long Valley Caldera (shown in a 3-D image produced by the NASA/JPL SIR-C Synthetic Aperture Radar aboard the Space Shuttle *Endeavour*) covered what is today the southwestern United States with a blanket of ash that extended as far east as the Mississippi. The region is still active, with the last sizable eruption occurring about 250 years ago. This view looks north, along the northeastern edge of the caldera.

Joe, you've made in-depth studies of ancient geological upheavals. Can you put these recent events in perspective for us?

JK: Just to take volcanoes, the Icelandic eruption that we saw this spring was *tiny* compared to eruptions that have happened previously in Earth's history. In California alone, about three-quarters of a million years ago—which geologically is nothing—the Long Valley Caldera, between Mono Lake and Mammoth, blew its top. The eruption covered the southwestern United States with a blanket of ash that extended all the way to the Mississippi. The sediments that washed off from the Mississippi delta produced deposits that in some places were hundreds of meters thick. That episode was far, far worse than anything in human memory. There was a similar eruption about two million years ago in what is today Yellowstone. The source was Huckleberry Ridge, and the ash, again, blanketed everywhere.

You know, as a geologist, I find these events useful because you can go to sediments of that age, and when you see evidence of the Huckleberry Ridge or the Long Valley Bishop Ash eruptions, you know exactly where you are chronologically. They are signature events that we can correlate and use to tell the age of the sediments that contain them. But it's sure not something that you would want to have happen anywhere near you today. There are volcanoes like this in other parts of the world. One of them, Mount Sakurajima, on the island of Kyushu in Japan, blows its top quite often—most recently, just last year. You wouldn't want to be anywhere nearby when that mountain decides to get really mad again.

Climatically the Icelandic eruption didn't do much of anything—the damage it caused was almost entirely economic. It was nothing like major episodes in Earth's history where we've had volcanic eruptions that have destabilized the climate to the point where they produced mass-extinction events.

The biggest of these events occurred at what we call the Permian-Triassic boundary, a little over 250 million years ago. It is sometimes referred to as the Great Dying, because such a significant percentage of life on Earth was wiped out over a period of some 15 million years. Today in the geologic record, we find evidence of flood basalts that covered Siberia and perhaps huge volumes of the surrounding ocean floor. The chemical reactions with the volcanic outflows and gases depleted the oceans so severely of oxygen that they basically went anoxic and marine life suffocated. You can see the fingerprints of that in the fossil record. And it's all linked to these enormous volcanic eruptions.

Hey—it's important to recognize that we're living on a dangerous planet. The one thing that you can say with near certainty is that if you go through the rock record and find evidence that something has occurred every 10 or 20 million years, it's going to happen again. It just happens that we're living in a very nice interval right now, and we wouldn't want to go back to any of these other periods.

"The one thing that you can say with near certainty is that if you go through the rock record and find evidence that something has occurred every 10 or 20 million years, it's going to happen again."

One question we often hear from both the public and the media is, will we ever be able to predict earthquakes the way we can—more or less—forecast the weather? What are your views?

HK: There are such fundamental differences between weather forecasting and earthquake prediction. With weather, the situation basically changes on an almost daily basis. With quakes, we are dealing with long-term processes in which the timescale for stress buildup and release is very long—100 to 1,000 years or more—while the length of time in which quakes occur is very short.

As I said earlier, we have made major advances in our understanding of how these seismic processes operate over these lengthy timescales. But to be able to say there's a strong likelihood that a magnitude

“Why are we supporting this thing called the geological survey to study volcanoes?”

8 earthquake will occur in some specific area within the next hundred years or so is not necessarily very useful for the average layperson. You simply can’t handle it like a weather forecast. If the forecast says, “rain tomorrow,” you may take your umbrella, and either it rains or it doesn’t. However, in the case of earthquakes, if you say that something big is going to happen tomorrow and nothing happens, that can be a problem. And that’s really a key difference between climatology and seismology.

JK: I agree with Hiroo. If you want to see how completely distinct the two areas are, just turn the analogy around. Certainly, meteorology averaged over a very long period of time gives you climate. Or, to put it another way, climate is just long-term weather. But I certainly wouldn’t advocate analyzing ancient climates to determine whether you’ll have a thunderstorm next Tuesday.

HK: The fact is that it will be a long time, if ever, before we can accurately predict when and where major earthquakes will occur. So the real question is, if we are becoming more adept at gathering and interpreting information about long-term seismic conditions and so forth, how can we make the best use of it?

What we really need to emphasize are rapid-response systems and structural-control systems, so that when significant earthquakes happen and these large seismic waves are generated, we are able to capture that activity, analyze it, and prepare structures that are better able to withstand shaking. You cannot make very precise, short-term predictions, but there are certainly more effective and efficient ways to capitalize on the information we do have.

It’s so important to have scientists working directly with engineers on these issues so that we can give them a good idea of what to expect over the long term. Then they can apply that knowledge to come up with better ways to deal with natural hazards and their potentially damaging impacts. We have made a great deal of progress in civil and structural engineering, and it’s exciting to see that our scientific product can be effectively used for the public benefit. But there is a great deal more we can and should be doing.

JK: We also need to do more to raise public awareness and understanding of why it is so essential to invest in this research and these technologies. Earlier this year we had some politician stand up and ask indignantly, “Why are we supporting this thing called the geological survey to study volcanoes?” Then, of course, boom! Iceland goes off and you disrupt the entire economy of Europe. Maybe that makes the reasons even more obvious, but we shouldn’t have to rely on these kinds of wake-up calls to make the point that the planet’s seismic and climatic activity merits serious study, and must be supported by both public and private sources. A system in which science is left to wither and die is not a way of maintaining your civilization. I may be a geologist, but I don’t want to go back to the Stone Age, thank you. E&S

***Hiroo Kanamori*, the Smits Professor of Geophysics, Emeritus, was the director of Caltech’s seismo lab from 1990 to 1998. Born in 1936, just 13 years after the magnitude 7.9 Great Kanto Earthquake that devastated the Tokyo-Yokohama area and killed some 140,000 people, Kanamori earned his PhD at the University of Tokyo in 1964. He then came to Caltech as a research fellow for a year, returning as a full professor in 1972. He became professor emeritus in 2005.**

***Joseph Kirschvink*, the Van Wingen Professor of Geobiology, studies biomagnetism, paleomagnetism, and Earth’s climatic history. He earned both a BS in biology and an MS in geology from Caltech in 1975, and a PhD in geobiology from Princeton in 1979. He returned to his alma mater as an assistant professor in 1981.**

Heidi Aspaturian, associate editor of* On Campus *and media relations writer from 1985 to 1992, editor of* On Campus *from 1993 to 2001, and editor of* Caltech News *from 1992 to 2009, recently retired from the Caltech Office of Marketing and Communications.

From glaciers at the equators to dinosaurs near the poles, listen to Joe Kirschvink discuss Earth’s ancient climates in an exclusive* E&S *podcast.

Sex, Flies, and Videotape

By Douglas L. Smith

A lunging fly looks angry, but the "emotion" is a hard-wired reflex. Now a computer-vision system that watches flies and can figure out what they're doing is helping biologists trace those wires—and might one day be able to read human emotions.

How deep does emotion go? When fear trumps reason, pop psychologists tell us it's the older, reptilian part of our brain taking over. But what brain circuits are really responsible, and how are they wired up? To answer this very big question, a Caltech neurobiologist, a computer scientist, and a bioengineer have started very small—with *Drosophila melanogaster*, otherwise known as the common fruit fly.

The fly's tiny brain contains only about 40,000 nerve cells—not counting the optic lobes, which include another 60,000 or so—and, to a first approximation, is more or less hardwired, says biologist David Anderson. "We do not have anything *close* to a complete wiring diagram, but when you look at the major branches in a neuron's dendritic tree and where those branches go, they seem to be remarkably constant from one fly to another." So, like a person in a strange house flipping the switches in the front hall to find out where the lights are, Anderson is turning specific nerve cells on and off to see what happens.

The seeds of Anderson's work were planted at Caltech in the 1960s. While researchers elsewhere were teaching mice to run mazes, biologist Seymour Benzer began mutating flies to induce behavioral oddities—establishing what has become a very fertile field. As flies have a generation time of only 12 days (versus some nine weeks for mice), the experiments proceeded at a gratifying pace, and his lab discovered a host of genes responsible for controlling such things as how flies responded to light, when they slept, and whether they mated. Although Benzer formally retired in 1992, he continued working right up to his death in 2007.

When Anderson got interested in the neural-circuitry problem about a decade ago, he intended to study mice, and he and biologist Henry Lester began developing a set of techniques to turn mouse neurons on and off. "But I had always had fly envy," Anderson says. "I spent a lot of time talking with Seymour about whether one could study primitive versions of emotion-like behaviors, like fear, in flies. And there are a lot of fancy genetic manipulations that you can do in flies that you can't do so easily in mice." Around 2005, "after spending three or four years really struggling to get the mouse system under way, we decided to initiate a program with flies. So the reason I started with them—in addition to sheer impatience—is the potential to screen thousands of lines of genetically altered flies to look for behavioral changes."

FEAR AND AGGRESSION IN PASADENA

Anderson also eventually switched his focus from fear to aggression. "When people see videos of flies fighting, they don't have to be convinced that this is analogous to an emotional behavior in humans. It's harder to show that a fly is afraid of something. There's a quote from Charles Darwin's 1872 book, *The Expression of the Emotions in Man and Animals*, that I love: 'Even insects express anger, terror, jealousy, and love by their stridulation.' Now, this doesn't mean that I think that flies get angry when they fight, or feel anything like anger. When we talk about 'emotional behavior' in animals, we're talking about an observable motor behavior, not a subjective state that might accompany such behavior."

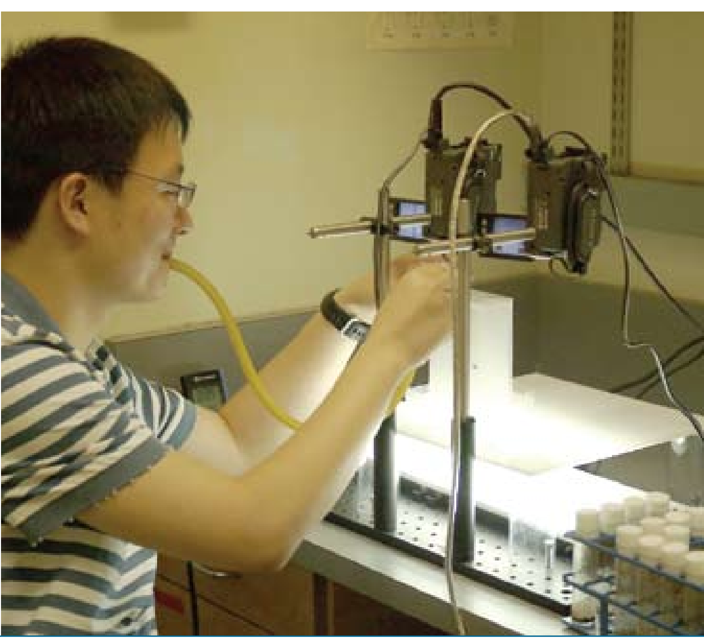
These subjective states, however, are very much on the mind of machine-vision expert Pietro Perona. Since the mid-1990s, Perona has been trying to figure out how to teach computers to look at people, read their emotions, and divine their intentions—something humans do instinctively. (See "The Machine Stares Back," *E&S* 1999, Nos. 1/2.) Besides leading to some truly awesome video games, such a system could be used by market researchers to find out what people really think of a product being pitched to them, or by security cameras to decide whether that nervous-looking fellow in the ATM queue is a potential armed robber.

But when an action as simple as walking looks so different in front and side views, good luck trying to codify the distinction between a joyous strut and a furtive skulk. "How can I decompose human behavior into meaningful motions, which are its fundamental ingredients?" says Perona. "I realized at some point that I had to study behavior in a simpler setting, and David convinced me that flies have an enormous repertoire of interesting behaviors. Flies are very simple animals and their bodies are extremely easy to track. You can put a camera on them and watch them as they fight, as they court, as they mate, as they look for food."

Anderson was also talking with Michael Dickinson, a zoologist-turned-engineer who had been deconstructing *Drosophila*'s flight-control systems with an eye toward designing free-flying microrobots. (See "Come Fly with Me," *E&S* 2003, No. 3.) A fly can flap its wings 250 times per second, and it can change its course by 90 degrees in 50 milliseconds, so Dickinson's lab was shooting high-speed videos of individual flies on the wing. A computer processed these videos to reconstruct each wing's motions in three dimensions, but only after a live human had gone through the footage, one frame at a time, to trace the outlines of the wings' silhouettes. But Dickinson's interests were shifting from the fluid dynamics of flies in midair to the group dynamics of flies in large numbers, which would mean tracing dozens of flies at once.

Both Anderson and Dickinson envisioned the same strategy: put some flies in an "arena"—a rather grandiose term for an enclosure that might range in size from a postage stamp to a dinner plate—mount a small camcorder overhead, like the Goodyear blimp looking down on the 50-yard line at the Rose Bowl, and ask a computer to report on what the flies are doing. The computer, working tirelessly, would analyze thousands and thousands of hours of video to create vast databases of fly behavior that could be mined statistically.

But the two sets of software specs that resulted were nearly polar opposites. Anderson needed to watch pairs of flies in close quarters and catalog each occurrence of any of an assortment of predefined aggressive or courting actions—Perona's "meaningful motions," which, when performed in various sequences, add up to the complex behaviors we put names to. Dickinson wanted to follow 50 individual flies out in the open simultaneously, keeping each fly's identity straight while mapping its path. His software needed to classify the fly's movements into a few broad categories—Was it walking forward? Backing up?—but the main purpose was to reveal patterns of social interaction.



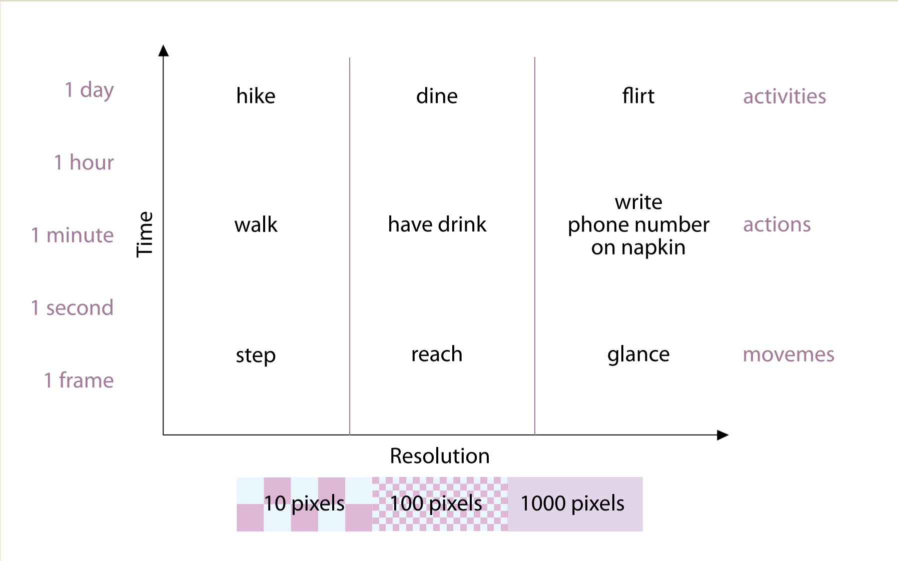
Anderson's grad student Liming Wang stocks an arena—the tall rectangular container underneath the leftmost camcorder—with a pair of flies from one of the vials at right. A fluorescent lightbox illuminates the arena floor from below, creating a clean, uniform background that makes it easier for the computer to find the flies. He is ferrying the flies with an aspirator, which is basically a length of surgical tubing with a plastic tip.

EYES ON THE FLIES

Back in 2005, the state of the art in behavior tracking owed more to the sweatshop than the supercomputer—grad students and postdocs watching endless hours of grainy video and making tick marks on pieces of paper whenever fly X lunged at fly Y. Each video was only 20 minutes long, but if you factored in all the scrolling back and forth to mark the exact frame where every lunge began and ended, then completely cataloging just the lunges could take well over an hour. If you also wanted to count the chases, or the touches, you had to go back and rewatch the entire video all over again.

Not only is this mind-numbingly boring, it's error-prone. Besides the obvious ways

WHAT IS “BEHAVIOR,” ANYWAY?



Perona’s ultimate goal is to build a computer that interacts with us the way we do. “We look at each other, and I know you’re sitting comfortably and I know you’re paying attention to me, taking notes,” he explains. “That’s very useful for me and I would like a machine to be able to do the same.” Perona picks up all this information intuitively, with a glance at body language and facial expression, but a computer needs things to be spelled out for it. Figuring out what we need to tell the computer brings up a very basic question—what do we mean by “behavior” in the first place?

It turns out that we mean many things, as the chart at right shows. We tend to think in terms of long-term behavior, which we describe at a very high level. “That man is out to pick a fight,” a pool-hall bouncer might say. But this abstraction is based on observing concrete activity—the belligerent fellow has been getting drunk for the past hour, and is now sliding off his bar stool and heading for the biggest dude in the room. Activity, in turn, is a collection of individual actions that might take a minute or less each—chugging a beer, for example. And at the very lowest level, an action can be broken down into a sequence of movements—reaching for the mug, gripping the handle, rasing the brim to the lips, tilting back the head and arm, and slamming the empty down on the bar.

These are the “meaningful motions” Perona is looking for, which he calls “movemes” by analogy to the phonemes that are the fundamental sounds of speech. A lisped “s” is still an “s,” and someone speaking English with a German accent may inject a little extra phlegm into the “ch” sound, but the meaning is still clear. Similarly, a reach in any direction is still a reach, even if it’s a sloppily executed one that winds up spilling half the mug.

In other words, movemes are the building blocks of behavior that can be described in such a way that they make sense to a computer, when all the machine has to go on is a video feed that it can examine frame by frame to see if any of the pixels have changed.

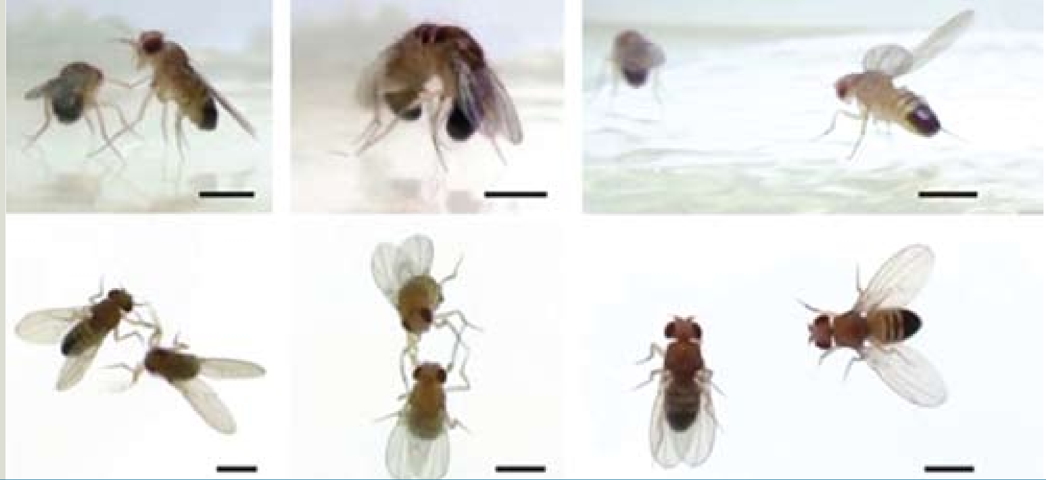
This brings us to the chart’s horizontal axis—seeing a behavior takes various amounts of pixels, as well as different lengths of time. Some movemes will be obvious even at very low resolutions. “If you punch somebody,” says Perona, “I may see that even if your whole body only appears in 10 pixels. You could be very far away, just a ghost in the distance. But if you wink at me from across the room, I may need to put a thousand pixels on your body to be able to see that eye motion. So there are multiple scales of resolution in time and space that are meaningful to us.”

Substituting fruit flies for humans has allowed Perona to explore this notion of movemes using a creature with a much smaller vocabulary of gestures. “We have made quite a bit of progress in understanding how to think about these problems,” he says. “What is the signal that is there in images? How do you harvest it? And how do you decide if something is happening?”

When these problems are eventually solved, Perona says, we could wire up “smart homes” for the elderly who live alone, where a computer automatically calls 911 if you’ve fallen and you can’t get up, or summons your doctor if you look a little green. Factory floors and construction sites could be made safer, since “every move of every worker could be followed and evaluated for risk, and the worker could be briefed at the end of the day on better safety practices.” And, of course, there’d be the killer iPhone apps. “Your cell phone might one day be able to tell you what’s wrong with your golf swing, and maybe give you tips on your tennis backhand as well.” *—DS*

Right: Top and side views of three things CADABRA is programmed to recognize. Going from left to right, we see a lunge, a tussle, and a wing threat.
Below right: The computer extracts the fly's image from the background pixels, then fits an oval around the fly's body.
Bottom right: Some of the parameters CADABRA calculates for every encounter between a pair of flies. The scale bars are one millimeter long.

All figures from Dankert, et al., *Nature Methods* 6: 4 (2009)
© Macmillan Publishers Ltd.



to miss something—an ill-timed sneeze, a ringing phone, or simply zoning out for a few minutes—behavior can be in the eye of the beholder. Says Perona, "How long does one fly have to follow the other for it to count as 'following'? At what distance should they be? How fast should they be going? If somebody in Norway made an observation, and I am trying to reproduce it here, how do I know that I'm observing the flies in the same way?"

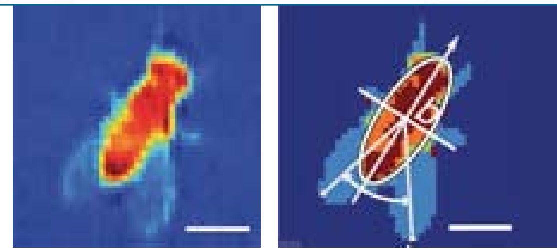
"I had two biologists labeling my frames," remarks Perona postdoc Piotr Dollar, "and they only agreed on about 72 percent of them. And when I had the same person relabel some of them two months later, there was only about 80 percent agreement" with that person's previous set of observations. It wasn't merely a matter of changing one's mind on where an action started or stopped, either—"entire behaviors would be missing."

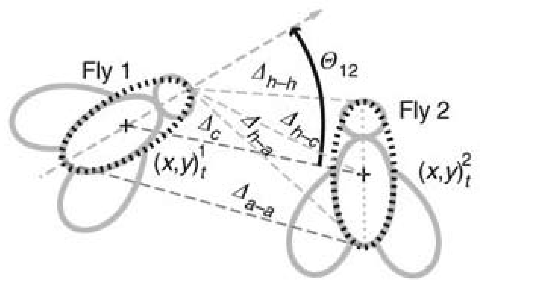
Since computational techniques for identifying dark objects on a bright background (or vice versa) are well established, as are methods for following those objects from one frame of a video to the next, Perona figured it might take about three weeks to write Anderson's and Dickinson's software. In fact, the first draft of each package took more than a year. Finding the flies and keeping track of them was the easy part; "the big difficulty was keeping the flies distinct when they were bumping into each other and overlapping," says Perona. It also proved harder than expected to make systems that would run reliably in the hands of people who were not computer scientists.

The first step was bringing the video-labeling process into the electronic age, with a captioning package not unlike the video-editing software you might have on your PC. "There was a commercial system available, but it wasn't terribly good," says Perona. "So we had to write one from scratch." As a fly movie plays in one window, another window displays a separate time track for each insect. Clicking on the time track allows you to mark the frame where, for example, the fly begins its lunge. "We would play the video at one-tenth speed, freeze it, click on a fly, and then choose a behavior from a dropdown menu," says Liming Wang, a grad student of Anderson's.

Hundreds of hours of meticulously annotated video would be fed to the computer, which could then teach itself what a lunge looked like by scanning the database, watching all the segments marked "lunge," and extracting some set of parameters common to all the examples. Once the computer had processed this "training set," the researchers would give it a fresh set of videos, the test set, for it to label on its own. Of course, the humans had to check its work, which meant that all of the test set's videos had to be labeled by hand as well. And then the process would repeat. Endlessly.

It took about three years of machine learning to get ready for prime time, but the finished products debuted last spring. Both software packages can be downloaded for free, and they are now in widespread use. The one for watching pairs of flies—the cage matches, if you will—is called CADABRA, for Caltech Automated *Drosophila* Aggression-Courtship Behavioral Recognition Algorithm. It was created by Heiko Dankert, a postdoc working with Perona and Anderson; Wang; and Anderson postdoc Eric Hoopfer. The other, which records and displays the meandering paths of large groups of flies in an open field, is named Ctrax—pronounced "See-tracks," get it? It was developed independently by postdoc Kristin Branson, working with Perona and Dickinson, and Dickinson's grad students Alice Robie (PhD '10) and John Bender (PhD '07). CADABRA and Ctrax were published in the April and June 2009 issues of *Nature Methods*, respectively. (Dickinson has since joined the faculty of the University of Washington in Seattle.)





CADABRA: MAKE LOVE, OR WAR

The behaviors that CADABRA automatically recognizes include three that are explicitly aggressive: the "tussle," in which flies sumo-wrestle by facing each other, gripping one another with their forelegs, and struggling to displace their opponent; the "lunge," in which one fly rises up on its hind legs and pounces on its opponent; and the "wing threat," in which both wings are extended perpendicular to the body and then tilted up about 45 degrees, presumably to make the fly appear bigger and more intimidating. Three others are courtship-related: "circling," in which the male fly walks sideways around the object of his desire, facing head-in; "wing extension," in which our suitor woos his intended by vibrating an outstretched wing in a courtship song; and "copulation," over which we shall draw a discreet curtain. The final one, "chasing," can lead to either sex or violence, depending on the circumstances.

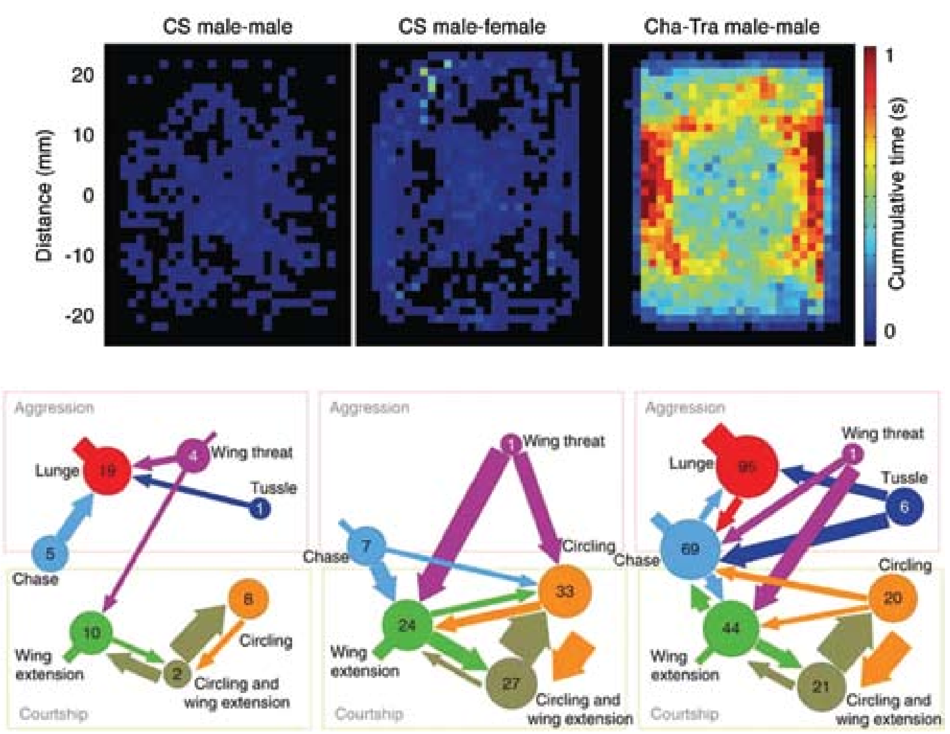
CADABRA scrolls through the video frame by frame, locating and identifying each fly. (Females are bigger than males, making it easy to keep straight who's who; when male flies are paired up, one of them gets a

Figuring out which way the fly is facing provides critical information, as butting heads and bumping butts are likely to lead to very different outcomes.

drop of white paint on his back.) Then the software analyzes each fly's pose—creating a mathematical representation of its body language. The process begins by breaking each fly down into three ovals: one for the body and one for each wing. The wings are a different shade than the body, and thus easily distinguishable. Figuring out which way the fly is facing provides critical information, as butting heads and bumping butts are likely to lead to very different outcomes. Fortunately, fly heads are quite shiny due to their reflective, waxy cuticle, so the computer divides the body oval in two and labels the brighter half the head. Then the system calculates a set of 25 parameters, starting with the fly's position, velocity, and direction of travel and going into such details as the body's apparent length, its angle of orientation (which is not necessarily the same direction it is moving), and the angles of the wings to the body.

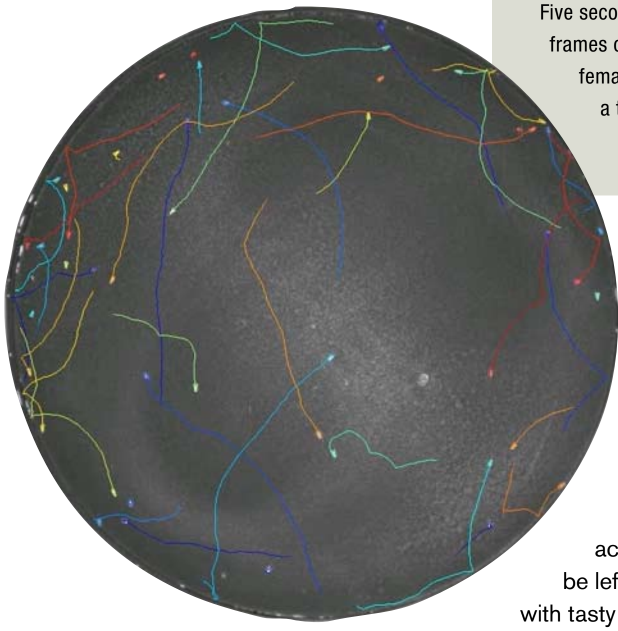
"Heiko, Pietro, and I watched a whole bunch of movies and made a big list of what parameters the system needed to look for," says Wang. "In a lunge, for example, when the fly rears up to strike, it gets smaller as seen from above. When it lunges, the head suddenly accelerates. And before it lunges, it often stops, to sort of gather itself. It follows its opponent, then pauses, then lunges." It usually took 10 to 15 of the 25 parameters to describe each behavior, Wang says. If the action was simple enough, the biologists could even define it explicitly—for example, in a wing extension, the wing had to be outstretched between 60 and 90 degrees from the body for at least one second. This precision was alluring, but the more complex activities eluded such easy encapsulation. All the biologists could do then was label the videos and leave the machine to figure things out for itself.

CADABRA's analytical power comes from its ability to compile videos into "stacks" that can be compared to other stacks. A stack could be a "heat map" that shows where something tended to happen; for example, fights were most likely to break out at a food source placed in the center of the arena, causing that area to glow red. Behavioral differences started to pop out immediately. Males from a strain of flies called Cha-Tra, whose brains have been "feminized" by messing with the genes that control masculine development, spent an awful lot of time chasing each other around the arena's periphery. Pairs of unmutated, or "wild-type," males were more venturesome, and were as likely to chase each other out in the middle of the arena as they were to hug the walls. Timelines can be stacked just as easily. "Flies fight a lot in the first 10 minutes," Wang says. "After that, they seem to get to know each other. Or they get bored. We don't know."



Dankert, et al., *Nature Methods* 6: 4 (2009) © Macmillan Publishers Ltd.

Top: A trio of CADABRA heat maps. The hotter the color, the more time pairs of flies in that location spent chasing each other. CS (for Canton-S) flies are a standard strain of unmutated flies. They went their own way most of the time, but their few chases were fairly evenly distributed throughout the arena. Pairs of Cha-Tra males were much more likely to chase each other along an arena wall. Bottom: CADABRA ethograms for the same pairs of flies. The size of each circle, and the number in it, reflects how often each action occurred. The relative widths of the connecting arrows show what was most likely to happen next. (In order to qualify as related, the two actions had to be separated by 10 seconds or less.) The stubs show the probability of the same action being repeated: thus, if a Cha-Tra fly lunged, it was likely to lunge again. Twenty pairs of CS males, 24 male-female pairs, and 10 pairs of Cha-Tra males were recorded in this set of videos.



Branson, et al., *Nature Methods* 6: 6 (2009) © Macmillan Publishers Ltd.

Five seconds' worth of Ctrax data—100 frames of video—for 50 wild-type female flies. Each fly is marked by a tiny triangle that draws a line showing where it's been.

Most importantly, CADABRA can create the behavioral equivalent of a traffic-pattern diagram. Called an ethogram, it maps how actions flow into one another. For example, when wild-type males were paired up, a chase was usually followed by a hostile lunge. But put two Cha-Tra males together, and they were as likely to become lovers as fighters, with a chase leading to an amorous advance in the form of a wing extension as often as it did to a lunge. Such analyses might reveal whether aggression and courtship are at opposite ends of one continuum, controlled by a dimmer switch—the level of one or two critical proteins, perhaps—or whether they're really two different states of mind, if flies can be said to have minds, controlled by two independent neural circuits.

With CADABRA up and running, the Anderson lab has shifted into high gear, screening 100 different strains of flies per week, and recording a dozen pairs of flies per strain. Fully annotating seven actions per video would have soaked up more than 80 person-hours per strain—two entire work weeks for some poor grad student. CADABRA does the entire analysis in a few minutes.

CTRAX: FACES IN THE CROWD

Ctrax, created for the Dickinson lab, monitors groups of flies wandering as the whim takes them in an arena 10 inches in diameter—scaled to the length of a fly's body, that's about a mile across. This vast landscape can be left empty, or it can be strewn with tasty tidbits at which to gather (or fight), obstacles to explore or navigate around, pinnacles to climb, or anything else the researchers can come up with. "It is a bit of a fishing expedition," Perona says. "If the machine can look at kilometers of footage and detect some regularities, it may be able to formulate a hypothesis that a biologist hadn't yet made." And there may be behaviors that are so rare humans might not see them, or that take so long to play out we would not realize that they are happening.

Postdoc Kristin Branson faced an enormous challenge when writing Ctrax. How could she keep each fly's identity straight without having to attach a physical marker to the insect, as the best commercially available package did? Other systems that didn't use markers were prone to confusion when the flies got close together, and would often misassign their IDs when they parted ways again. Ctrax minimizes identity theft through frame-by-frame comparisons. It first looks at each frame in isolation and tries to locate all the flies it can by using what Perona postdoc Michael Maire calls a "blob detector." Then, working on the assumption that each fly won't have moved much, it compares consecutive frames to see whether a blob appears in roughly the same spot and is moving in a smooth path. If the blob is too big, the computer subdivides it by fitting fly-sized ellipses to contiguous groups of pixels. (Even if the flies are climbing over one another, there's usually a gap of a few pixels' width between some portion of their overlapping silhouettes.)

Backtracking along each ellipse's path tells Ctrax which end of each blob to call the head—flies are more likely to be walking forward than backward. Flies don't usually enter or leave the arena, so if a track suddenly vanishes during the rewind, the computer looks around for other tracks. If a nearby track dead-ends, for example, perhaps it and the vanishing track should be spliced together. Or perhaps a track forks, and the vanished track can supply the missing leg. The system can get stumped if, for example, a fly rears up and appears foreshortened, or makes an abrupt move in a radically different direction. Ctrax then calls for help, asking a human to look at the video and fix things by hand. "This happens once every fly-hour or so," says Perona.

Once the processing is complete, Ctrax displays each fly as a thin triangle—the pointy end being the head—trailing a colored line that traces its path. The line usually just shows the last little bit of the fly's history; otherwise, the arena quickly fills with a rainbow of scribbles resembling the work of a bored five-year-old with a fresh box of Crayolas.

The arena quickly fills with a rainbow of scribbles resembling the work of a bored five-year-old with a fresh box of Crayolas.

Dickinson's lab trained Ctrax to recognize walking, stopping, turning sharply, backing up, jumping, chasing, touching, and crab-walking, in which the flies move sideways. Then they gave the system a workout, using 17 groups of 20 flies each: all-male contingents; all-female ones; 50-50 mixes; and batches of male flies with the *fru* mutation, which controls male courtship and mating. By creating an ethogram for each individual fly, Ctrax could automatically determine its gender (and, in the case of the *fru* flies, its phenotype) with better than 95 percent accuracy. Male flies proved to have little sense of personal space, routinely approaching other flies of either sex until little more than a body length separated them. Females were more retiring, preferring to keep at least two body lengths between themselves and others. And *fru* flies were far more likely to back away from an encounter than were wild-type males.

Each wild-type fly displayed its own self-consistent neural programming. Some flies kept close to the walls, while others ventured out into the center more often. Each fly had a preferred walking speed—the zippiest striding twice as fast as the pokiest—and a favorite duration for its strolls. Even the percentage of time a fly spent moving around versus standing still was an individual trait.

Ctrax's ultimate validation came when it flagged large numbers of track segments that defied classification. When the humans reviewed them, several new behavior types were identified: T-stops, X-stops, jousts, drag races, and even games of chicken.

FROM SLEDGEHAMMERS TO THERMOSTATS

Seymour Benzer's groundbreaking work back in the 1960s had used a sledgehammer approach, zapping the flies with X rays or dosing them with chemicals to induce wholesale mutations. The screening process was quick, thanks to ingenious methods his lab developed to collect the flies displaying some desired behavior. The time-consuming part of the job came afterward: inventorying the mutations each fly carried and then trying to figure out which one actually made the difference.

Nowadays, Anderson turns neurons on or off as easily as flicking a light switch—or, rather, adjusting a thermostat, thanks to a nifty piece of molecular biology developed at Brandeis University by Paul Garrity (PhD '93). The procedure exploits a temperature-sensitive ion-channel protein called TrpA1, for Transient Receptor Protein A1, which is normally found in heat-sensing neurons that help the fly stay in its comfort zone. Flies like it a bit on the chilly side, so TrpA1's ion channel stays squeezed tightly shut at 22°C, but unclenches at 27°C—the equivalent of taking the flies' cage from an air-conditioned lab out into a nice summer afternoon. When the channel is closed, the neuron can't fire. When the channel opens, the neuron goes off, telling the fly to start looking for a cooler place to hang out.

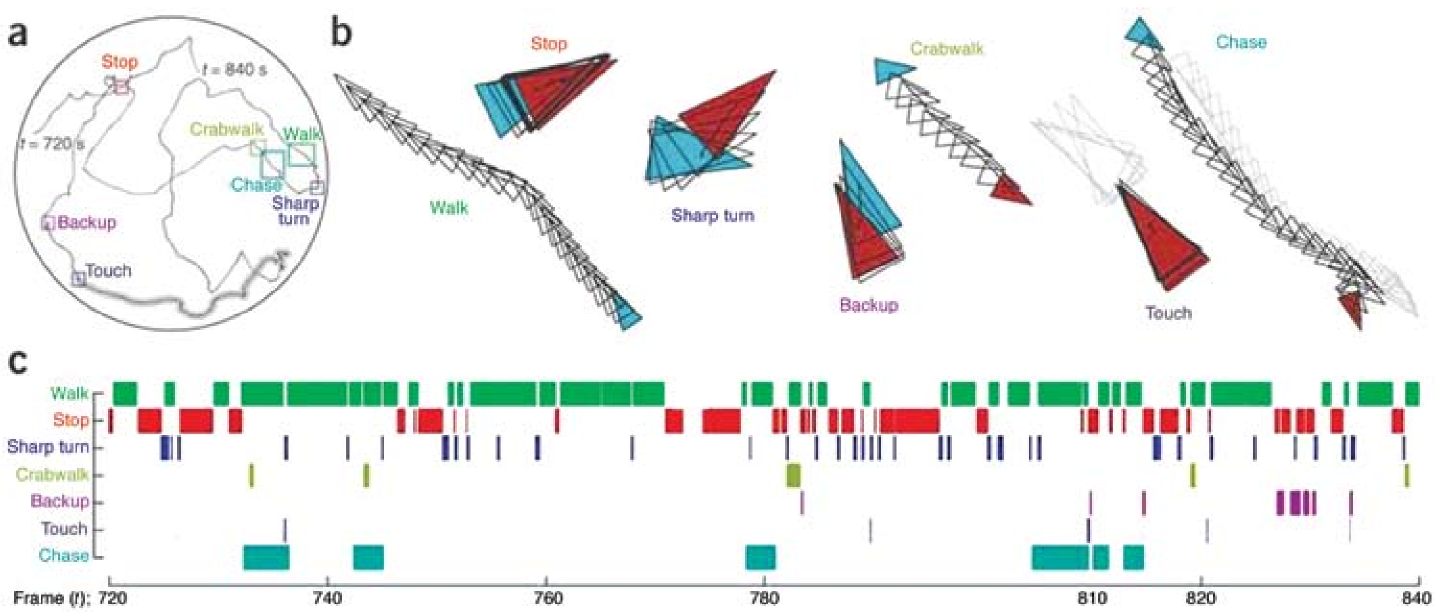
An extra copy of the *TrpA1* gene can be inserted into a fly's DNA globally and selectively activated in some specific set of neurons that are not normally heat-sensitive. The details are complicated, but depending on the type of neuron you choose, you can tweak a set containing only a few tens of cells. Other sets might have a few hundred, or perhaps a thousand neurons—still just a few percent of the fly's nonvisual brain cells.

The activated neurons proceed to sprout lots and lots of extra copies of the ion channel on their surfaces. At 22°C, the modified neurons go about their business as usual, firing at their normal rate whenever they're supposed to fire. When the temperature rises to 27°C, they still fire whenever they're supposed to fire. But because of all the extra ion channels, when they *do* fire, they just go nuts.

Traditional aggression screens have focused on genes, not neurons. These studies "knock out," or inactivate, a gene to see whether the resulting flies are less (or more) quarrelsome. But *over*activating a neuron and looking for flies with hair-trigger tempers has its advantages. "There are a lot of uninteresting, low-level ways to break a complicated behavior," says Anderson. "If the fly's legs don't work, they're not going be aggressive. But if you can specifically *enhance* aggressive behavior, there's much less likely to be a trivial or uninteresting explanation for it." And if the flies mellow out when retested at room temperature, "it tells us the increased aggression really is due to activating this particular subset of neurons, and not because those flies just happened to have had a bad day and were in a bad mood and fought a lot."

Studying neurons instead of genes has another benefit. If many genes are involved, which is likely, each one might make a small, subtle contribution. "But a neuron reflects the combined activities of whatever 12,000 to 15,000 genes are turned on in that cell," says Anderson. A pilot study of a couple

The colored boxes in this two-minute trace (a) of a male fly's movements through a coed crowd show seven behaviors that Ctrax labeled. In a close-up look at those boxed portions of the track (b), the triangles mark the fly's position in each frame. The blue and red triangles are the beginning and end points Ctrax assigned to the action; in the "walk" example, only the beginning point is shown. Gray triangles indicate the presence of a second fly. Plotting these actions against time (c) creates a visual summary of the fly's activities.



Adapted from Branson, et al., *Nature Methods* 6: 6 (2009) © Macmillan Publishers Ltd.

*Over*activating a neuron and looking for flies with hair-trigger tempers has its advantages. "There are lots of uninteresting, low-level ways to break a complicated behavior," says Anderson. "But if you can specifically *enhance* aggressive behavior, there's much less likely to be a trivial or uninteresting explanation for it."

hundred strains of flies showed that in the few that were extra feisty, "the increase is *very* big and *very* dramatic—by an order of magnitude. You don't need fancy statistics to see it."

Bigger studies are on the horizon. Anderson's postdoc Eric Hoopfer is now at the Howard Hughes Medical Institute's Janelia Farm Research Campus in Ashburn, Virginia, home to a collection of flies with overabundant TrpA1 channels in about 4,000 different sets of neurons. Hoopfer has adapted CADABRA to run on Janelia's supercomputer, and he plans to examine videos of every last one of those strains—the most comprehensive aggression screen ever attempted. "We're not making any assumptions about what *part* of the brain is involved in aggression," says Anderson, "or what *kind* of neurons are involved in aggression. We just test as many lines as possible. If some neurons keep showing up over and over again, or maybe look like they might be connected to each other, we can use this information to try and piece the circuit together. This software has really enabled an approach that could not previously have been undertaken."

OF MICE AND MEN

All through this past five years of fly work, Anderson never gave up on mice. "I like the idea of studying the same behavior in two evolutionarily very different species," he says. "Despite their obvious differences in brain structure, are there are some general principles that underlie the organization of aggression circuitry?"

We may be on the road to finding out. Perona postdoc Piotr Dollar is working on a generalized version of CADABRA that, alas, does not yet have a catchy acronym. Mice, being fluffy and flexible, are much harder for a computer to discern. They can curl up in a ball, or stretch out, or hunch over and scratch behind an ear. To make matters worse, this nearly infinite variety of "looks" has to be extracted from a textured background of wood shavings that registers in the same shades of gray.

Dollar has tackled such problems before. He used to work on the Caltech Pedestrian Detector, a program intended for cameras that could, for example, be mounted on airport shuttle buses. Such a system would be intended to alert the driver that someone is about to step out from behind a parked car and into the crosswalk ahead, and so it would have to deal with partially obscured bodies and blotty backgrounds all the time.

Says Perona, "Piotr figured out a very clever way, which is true progress in machine vision, for detecting the mouse." Dollar's system uses a collection of "weak" feature detectors, whose outputs are collected to render a verdict, Perona explains, and "his detectors are designed around sophisticated visual measurements that nobody had managed to use in practice before. It turns out that his method extends to almost any animal, and you can train it very easily." Says Dollar, "You just draw a little circle around the animal of interest in a few hundred frames, and then you also give the system a bunch of negative examples, which could be pictures of anything—you don't care."

Dollar is collaborating with Andrew Steele, a Broad Senior Research Fellow in Brain Circuitry, to test the system. "Getting something to work robustly in different lab environments is what makes the thing click," says Steele. "What separates a really great computer-vision person from someone who's merely good is that they give you something you can actually *use*. Because a lot of these papers that people publish only work with one database. They tune their algorithm to work really well on one type of video, in one lighting situation. And then it's not very useful for the end user like me."

Figuring out how to tell a mouse's head from its tail is going to take a while, however, and training the system for behavior recognition is still very much a work in progress. Anderson estimates that his lab—including a bunch of undergraduates on work-study—has invested 1,500 person-hours in annotating mouse videos.

But the payoff will be enormous. Says Anderson, "There are projects going on around the world—at the Sanger Institute in England, and at other sites—to generate a complete library of mutant mice in which each mouse has one, and only one, of its 20,000 genes inactivated. With a computer program analogous to CADABRA for mice, it would then be possible, in theory, to screen through all 20,000 mutants to see which ones have the biggest influence on aggressive behavior. And you would know in advance which gene was knocked out, which would be a *huge* advantage."

Brain function is as much about chemistry as circuitry, so Anderson's lab is also exploring the effects of pheromones and other chemical messengers such as dopamine. He's been doing this all along with the flies, but the mouse work could be adapted for what the biomed biz calls "translational science"—screening drugs to treat impulsive violence, for example. "We're not equipped to do it," Anderson says, "but it's something that the pharmaceutical industry might be very interested in doing." In the longer term, he adds, "current treatments for psychiatric disorders are very suboptimal. We have little understanding of what goes on in, for example, the brain of a depressed person, or how depression alters brain function. We need to understand the construction and function of the normal circuits that process emotional behaviors in order to understand how that function can become abnormal." e&s

Map by Veronica Olazabal for *Who's Watching? Video Camera Surveillance in New York City and the Need for Public Oversight* by the New York Civil Liberties Union, Fall 2006.

BIG BROTHER (AND EVERYONE ELSE) IS WATCHING YOU

A block-by-block survey of lower Manhattan conducted by the New York Civil Liberties Union in 2006 counted 4,176 security cameras between Battery Park and Fourteenth Street—and those were just the ones visible from the sidewalk. The city of London is said to have half a million of them, in public and private networks. "Right now, the cameras are mostly just videotaping, and storing the video," says Perona. "But in principle, you could network these cameras and automatically analyze what they are seeing."

Such automatic surveillance could discern forms of suspicious behavior too subtle for a human watchman to pick up at a distance. "Suppose you have a terrorist wearing a 30-kilogram explosive vest," says Perona. "He might walk in a slightly different way, because of the extra weight on the upper body." Other warning signs might slowly emerge over days or even weeks, eluding all but the most acute observers. "Say there's somebody sitting on a bench, pretending to be reading a newspaper, but taking mental notes for a future attack. If you observe the scene, there is nothing wrong with it. But if you see the same person the next day hanging around a phone booth, making a three-hour phone call, and on the third day, there they are again, sitting somewhere else, you will want to ask them what they are up to."

"These systems are coming," says Perona, "and they will be used. And the public needs to help regulate them in the proper way." —*DS* E&S

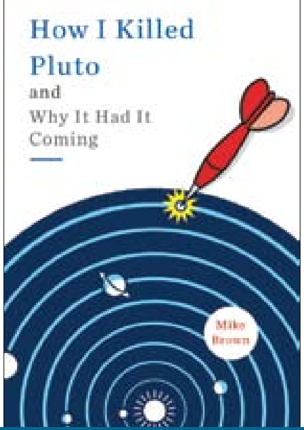
David Anderson is the Benzer Professor of Biology and an Investigator at the Howard Hughes Medical Institute. He earned his PhD at Rockefeller University in 1983 and came to Caltech as an assistant professor in 1986.

Pietro Perona is the Puckett Professor of Electrical Engineering. He earned his PhD at Berkeley in 1990 and moved south to Caltech the following year.

Michael Dickinson earned his PhD at the University of Washington in 1989. He arrived at Caltech as a visiting associate in 2001 and became a full professor here the following year. He was the Zarem Professor of Bioengineering at Caltech from 2003 to 2010.

On November 18, Anderson, Dickinson, and Caltech neurobiologist Christof Koch were named to the inaugural group of Allen Distinguished Investigators by the Paul G. Allen Family Foundation—seven scientists "working on some of the most exciting research in biology and neurology," according to Microsoft cofounder Paul Allen. (For more on Koch's work, see page 14.)

The CADABRA project was funded by the National Science Foundation, the National Institutes of Health, and an Alexander von Humboldt Foundation grant to Heiko Dankert. The Ctrax project was supported by the National Institutes of Health.



How I Killed Pluto and Why It Had It Coming
By Mike Brown
Spiegel & Grau
(Random House)
288 pages
$25.00

Mike Brown, Caltech's Rosenberg Professor and professor of planetary astronomy, reopened the question of what it means to be a planet in 2005, when he and his colleagues discovered an object out beyond Pluto that was bigger than Pluto. Since Pluto was a planet, surely their find—unofficially named Xena in a riff on the traditional Planet X and the Roman numeral for 10, as well as a nod to TV's imagining of Greek mythology—must be a planet too, right?

Despite the ominous title, there is much more to this thoroughly engaging and vastly entertaining blend of science and autobiography than Pluto's demise.

In a lovely bit of framing, the book begins in Huntsville, Alabama, with Brown—the son of a rocket scientist—as a first-grader who had a poster of the solar system on his bedroom wall, and ends with him sharing the wonderment and beauty of a moon-Jupiter-Venus conjunction in the evening sky with Lilah, his three-year-old daughter.

The chapters between lead off with a brief history of the solar system, focusing on the 19th-century bout of expansion that began in 1801 when Giuseppe Piazzi discovered Ceres wandering between the orbits of Mars and Jupiter. This era ended sometime around 1900, when Ceres, Pallas, Juno, and Vesta quietly joined dozens of their fellows as members of the asteroid belt.

Later, Brown's retelling of his early days in the field of planet-hunting includes a description of old-school astronomy, in which the first step in any project was locating one's quarry in the definitive sky atlas: the wall of filing cabinets holding the 1,200 fourteen-by-fourteen-inch photographic prints that make up the Palomar Observatory Sky Survey. Each print covers a roughly fist-sized patch of sky and contains millions of stars and galaxies. "Either you find the library ladder and climb to the top (if you're looking in the far north), or you sit on the floor (for the farthest southern objects)," he writes. After a hunt that might take an hour if the picture had been misfiled, you would hunch over a jeweler's loupe to find your target and take a Polaroid shot of the postcard-sized region surrounding it to use as a reference.

"For decades," Brown continues, "astronomers carried those Polaroids with them to telescopes all around the world. . . . In the control room of any telescope at any night of the year, you could find an astronomer or a group of astronomers holding a Polaroid print and staring at the TV screen. Often the actual image of the sky from the telescope was flipped or upside down and no one could ever remember which particular way this combination of instrument and telescope flipped images, so there would always be a time in the night when three or four astronomers would be squinting at a little screen full of stars, holding a little Polaroid picture full of stars, and turning the picture sideways and upside down until someone exclaimed, 'Ah ha! This star is here, and that little triangle of stars is here and we're in just the right place.' These days the technique is mostly simpler—the Palomar Observatory Sky Survey pictures are all quickly available over the Internet, and the cabinets full of prints are gathering dust; but because you can't take the computer screen and turn it sideways or flip it over, the little group of three or four astronomers is now more often than not standing with their heads cocked in all possible combination of directions until the lucky one exclaims, 'Ah ha!'"

After years of fruitless searching, the discoveries began in 2002—bodies provisionally named Object X (now officially Quaoar), the Flying Dutchman (Sedna), and Santa (Haumea), all of which at first potentially appeared to be bigger than Pluto, followed by Xena (Eris), which actually was. Underlying the cliffhanger—whether Xena/Eris would become the first new planet in 80 years, potentially opening the door of this once-exclusive club to perhaps hundreds of other claimants—was a subplot of foreign intrigue: the "discovery" of Santa/Haumea by a Spanish astronomer, José-Luis Ortiz . . . who, we find out, had been able to download Brown's unpublished coordinates from the telescope's pointing logs. (Ortiz, ironically, had earlier been a postdoc at JPL, leaving just before Brown arrived at Caltech as an assistant professor—one wonders what might have happened had the two become colleagues back then.)

The International Astronomical Union (IAU) settled Xena's hash relatively quickly by chucking Pluto of out of the planetary club at the August 2005 meeting; resolving the question of Santa's pedigree took until September 2008, when the IAU officially accepted the Brown team's proposed name, Haumea, but listed the Institute of Astrophysics of Andalusia as the place of discovery—without officially crediting either group for the sighting.

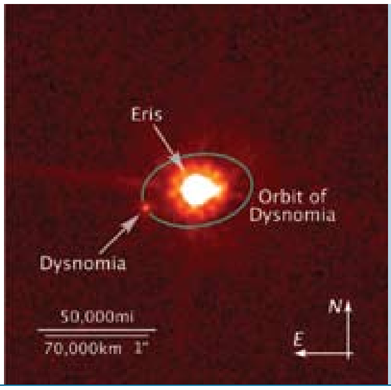
In some ways the best parts of the book are Brown's unabashed self-descriptions. We see geek love in all its glory, beginning with his non-courtship of Diane Binney, the leader of science-themed travel groups for the Caltech Associates who asked him to give a tour of the Keck telescopes in Hawaii. When a coworker pointed out that she seemed to be paying a lot of attention to him, Brown replied, "She runs trips for people; it's her job to be nice. I'm sure that all of the guys at Caltech that she has to work with get the wrong impression and make idiots of themselves. I'm not going to do anything stupid." Six months later, on the last night of the tour, Brown and Binney found themselves alone on the beach some time after midnight. Brown pointed out the Southern Cross and Saturn, and they talked. Writes Brown, "I was quite proud of myself for not having done anything stupid.

"When we got back to Caltech the following week, I found myself accidentally walking past Diane's office a few times a day and accidentally running into her and stopping to talk. Every time I did, she was very nice, and I had to remind myself that, truly, it was her job to be nice and to appear happy to see me and that being stupid was the worst thing to do. On accidentally running into her in the early afternoon one pleasant spring workday, I asked if she needed a cup of coffee. She did. We walked down the street, drank coffee, and talked for three hours. Certainly, it was part of her job to be nice to me and cultivate me as a good resource. But it occurred to me that, even accounting for all of that, there was no reason for her to spend three hours in the middle of an afternoon with me when we both had many other things to do. It suddenly occurred to me that, in fact, I had been stupid all along."

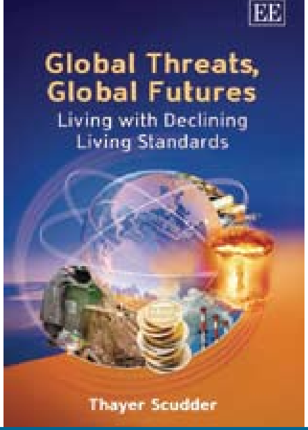
The discovery of the potential tenth planet, provisionally named Xena, coincided with Diane's pregnancy with their daughter, provisionally named Petunia. Xena was discovered in January 2005, just as it was about to go behind the sun, from whose glare it would not reemerge until September. Petunia was scheduled to appear on July 11, and the paper on Santa (discovered on December 27, 2004) was coming due as well. Brown slipped into hyperdrive, with one eye fixed on the calendar. "My goal was to get a paper on Santa finished before the birth of Petunia, since I still had a little free time. Her due date was now only three months away."

But how accurate *are* these due dates, really? Nobody he asked knew. "If I was at a dinner party with Diane and the subject of due dates was broached, Diane would turn to me with a slightly mortified look in her eyes and whisper, 'Please?' I would rant about doctors. About teachers. About lack of curiosity and dearth of scientific insight. . . . Inevitably the people at the dinner party would be friends from Caltech. Most had kids. . . . As soon as I started my rant, the fathers would all join in: 'Yeah! I could never get that question answered, either,' and they would bring up obscure statistical points of their own. The mothers would all roll their eyes, lean in toward Diane, and whisper, 'I am *so* sorry. I know just how you feel.'" There's no gender bias here: "My female graduate students wanted to know the answer to my question, too, and were prepared to rant alongside me."

Besides appealing to anybody interested in the solar system or astronomy in general, this book should be required reading for all members of the Caltech community, as well as anybody engaged or married to one. —*DS* e&s



On August 30, 2006, the Hubble Space Telescope took this image of Eris and its moon Dysnomia. By combining this image with another from the Keck Observatory, Brown calculated Dysnomia's orbit and Eris's mass, which is 27 percent larger than Pluto's.



Global Trends, Global Futures: Living with Declining Living Standards
by Thayer Scudder
Edward Elgar Publishing, 2010
304 pages, $40.00

When Adam Smith published *The Wealth of Nations* in 1776, he could never have imagined what would be done with the phrase "invisible hand," which appears but once in the entire work. A professor of moral philosophy, he retained an acute sense of the human costs of what that phrase symbolized. Nor did he hesitate to propose measures for ameliorating those costs.

Now, 234 years later, a book has arrived that could serve as a companion volume to Smith's *Principia* of political economy. If Smith explained how to most efficiently generate material wealth—a process today gone global—Caltech's Thayer Scudder, in *Global Threat, Global Futures: Living with Declining Living Standards*, provides a handbook not only for human survival, but for human flourishing in the face of threats that globalization either doesn't address, or that themselves are consequences of globalization.

Scudder, like Smith, brings to his analysis a deep knowledge of the human condition. A professor of anthropology, now emeritus, he has spent over half a century engaged in research and fieldwork, particularly studying poverty-stricken and displaced communities for extended periods of time. It is within the context of this experience that he examines issues of growth, sustainability, development, and quality of life.

A self-described "optimistic pessimist," Scudder believes that a worldwide decline in living standards is inevitable "not just in poor societies but in all societies and nations." Nonetheless, he believes that transformations are possible that could slow the rate and magnitude of such a decline.

The book's first three chapters detail the threats about which Scudder knows the most: poverty and the growing gap between rich and poor, fundamentalism of every stripe, and global environmental degradation. (By the end of the book he has also touched on population increase, urbanization, unsustainable levels of consumption, nuclear weapons, and global climate change.) He confesses himself "fascinated"—one senses *appalled* might be a more suitable word—that so few experts anticipated the current financial and economic crisis and that national and international leaders have proven so incapable of cooperating to address it.

In the next three chapters, Scudder undertakes case studies of the United States as a high-income nation, China as a middle-income one, and Zambia as low-income. Particularly disturbing is his list of U.S. economic, cultural, and educational weaknesses that "make America look increasingly like an inept third world country."

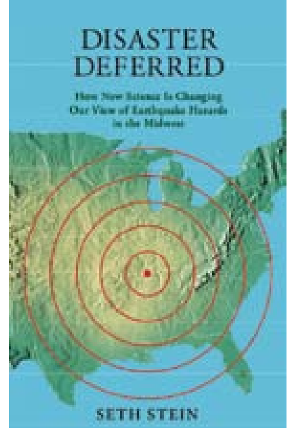
Key to the chapter on China is a study of the village Kaihsiengkung, "one of the longest long-term studies in anthropology," begun by Chinese anthropologist Fei Hsiaotung in 1936. The chapter on Zambia is grounded in Scudder's own work, principally his decades-long fieldwork with the Gwembe Tonga ethnic group.

Scudder takes great pains throughout the book to distinguish between living standards and quality of life and, analogously, between growth and development. It's not that he denigrates living standards and growth; rather, he feels they represent only part of the two broader concepts with which they are paired. Thus he defines development to include "access to a wider range of non-material attributes such as those available to people in every viable society and culture"—security, self-sufficiency, and self-respect, for example.

Especially in his case studies, Scudder illuminates the distinction between development and simple quantitative growth. In China, for example, a shift in the 1990s from a decentralized "household responsibility system"—which permitted private enterprise at the village level—to a more centralized emphasis on heavy industry and urbanization had the result that "personal income grew faster than GDP in the 1980s and slower than GDP in the 1990s."

An issue Scudder examines closely is that of *defining* poverty. He points out that, even with relatively little income, it's possible to have a satisfying life "based on dense networks of social relations and viable and resilient cultures that are only loosely attached to the market economy." He suggests that such communities may provide models for a future in which declining

Scudder illuminates a path, not only possible but plausible, through a destructive maze of humankind's own making.



Disaster Deferred: How New Science Is Changing Our View of Earthquake Hazards in the Midwest
by Seth Stein
Columbia University Press, 2010
296 pages, $27.95

living standards will be an issue.

Equally important is the question of categorizing poverty. Scudder discusses *relative* and *new* poverty—the former tied to the growing gap between rich and poor, the latter resulting from national and international programs that impoverish or displace formerly self-sufficient people. He also examines poverty associated with urbanization, failed states, and environmental degradation. Whatever its roots, poverty is a source of destabilization, disease, migration, and recruits for terrorist organizations. Scudder is particularly concerned with the extent to which policies of the United States and other Western countries and the World Bank have worsened poverty around the world.

When he discusses fundamentalism, Scudder focuses on three examples: Buddhist oppression of Sri Lanka's Tamil-speaking Hindu minority, the influence of extreme Jewish sects in Israel, and the impact of Christian fundamentalism on the U.S. government. He expands the definition of *fundamentalist* to include, for example, Western colonialism and the one-size-fits-all view of economies worldwide that currently dominates Washington, at which point his use of the word begins to seem perhaps more rhetorical than descriptive. Regardless, he makes a thorough case that fundamentalism is a force very difficult to control. Yet, in an ironic turn, he admits that a zeal akin to that of fundamentalism may be necessary to bring about the transformations he envisions as necessary.

Most heartfelt are his discussions of environmental degradation and its impact not only on biodiversity but on humanity itself. Scudder, who once considered ornithology as a profession, brings a deeply personal and poignant note to his discussion of bird decline, especially that of songbirds.

In his final chapter, "Transforming Global Societies," Scudder offers very specific suggestions for dealing with the threats he has cataloged. He emphasizes the empowerment of women (according to the World Bank, "societies that discriminate by gender tend to experience less rapid economic growth and poverty reduction"); the creation of a better balance between small-scale commercial agriculture and agribusiness; and the transformation of education. Regarding the latter, he considers the Children's Center at Caltech—which emphasizes hands-on learning, and which he and his wife, Eliza, have supported for many years—to be a model for preschools worldwide.

A work of political economy from the perspective of an anthropologist who has made a career of studying poverty and displaced people, *Global Threats, Global Futures* will prove rewarding reading for anyone concerned with issues of economic development, environmental and cultural degradation, and the causes and solutions of poverty.

Most of all, Thayer Scudder illuminates a path, not only possible but plausible, through a destructive maze of humankind's own making—if only the political will can be found to tread it. —*MF*

Between December 1811 and February 1812, four earthquakes of magnitude 7 or greater strongly shook the area along the Missouri-Tennessee border and surrounding states, ringing church bells as far away as Charleston, South Carolina. Such earthquakes violate the plate tectonic theory that earthquakes occur in zones between plates moving relative to one another: the New Madrid earthquakes—named after the town in what is now Missouri—occurred in the interior of the North America plate.

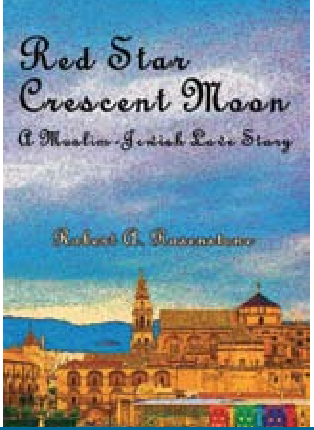
Seth Stein's fascinating book *Disaster Deferred* tells of scientists' attempts to understand this contradiction. The text is straightforward yet exciting: a high-school freshman can read it but a scientist of any discipline will be roused by it. The book is part story, part science, and part how scientists think.

In particular, Stein tells how the news media frightened hundreds of thousands of people with the prediction that a repeat earthquake would occur in December 1990 in New Madrid. Stein explains how and why the danger was overrated. He points out, furthermore, that risks posed by automobile accidents far outweigh those posed by earthquakes.

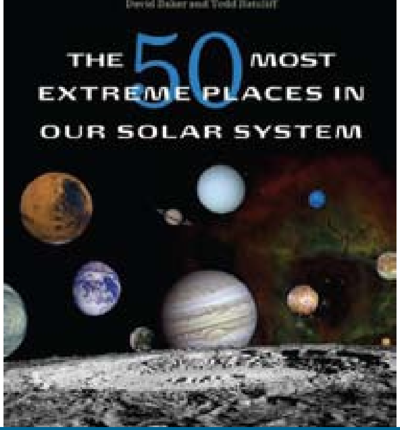
I would recommend this book to anyone interested in science.

Donald Argus is a principal scientist at JPL who uses satellite and ground-based methods to study how Earth's crust is reacting to the forces exerted on it by earthquakes, plate tectonics, melting polar ice, and other forces. Stein was one of Argus's PhD advisors at Northwestern University.

Red Star, Crescent Moon: A Muslim-Jewish Love Story
by Robert A. Rosenstone
Scarith, 2010
238 pages
$24.00



The 50 Most Extreme Places in Our Solar System
by David Baker and Todd Ratcliff
Belknap Press of Harvard University Press, 2010
304 pages, $27.95



In his career as historian, Robert Rosenstone has covered the globe of literary formats: pure history, historical reconstruction as fiction, the novel, the biography, and the autobiography. Rosenstone's first foray into fiction, *King of Odessa: A Novel of Isaac Babel*, melded the novel with biography. Having subsequently swum in the waters of autobiographical writing with *The Man Who Swam into History: The (Mostly) True Story of My Jewish Family*, Rosenstone has now returned to mixing and matching formats. This time he appears to have hybridized autobiography and fiction in *Red Star, Crescent Moon: A Muslim-Jewish Love Story*.

The novel's protagonist is Benjamin Redstone, a Jewish history professor who is serving as the historical consultant on a Hollywood film, *Red Star in Madrid*, based on his book *Crusade in Spain,* a history of the Americans who fought in the Spanish Civil War. The movie is being directed by megastar actor TJ ("The Most Beautiful Man in Hollywood") and shot in Spain. Redstone's love interest is Aisha, an Afghani-American filmmaker who is in Spain for a U.S. State Department–sponsored film festival highlighting American female directors and their work. Hers is *Far from Afghanistan*, a documentary about three refugee families in America after the Russian invasion of their country. Attractive and exotic, Aisha has lived in many parts of the world, but this is her first time in Europe. And as a Muslim, she is particularly interested in visiting the remains of 700 years of Muslim rule on the Iberian peninsula. Of course, Redstone is just the man to help her do that—a professor who has made some nine trips to Spain and is well versed—to say the least—in its culture and history.

Mixed into the storyline are Muslim terrorists taking hostages and raising the Islamic flag over the Calahorra Tower in Córdoba; assorted ex-wives; Islamic fundamentalists stalking the heroine; TJ taking great liberties with historical fact—as well as with every attractive woman who passes by; and several U.S. State Department apparatchiks wringing their hands over the leftish angle of TJ's film. Combining those elements with a format of chapters written from the points of view of different characters, and interspersed with news reports, makes for a novel that has something for everyone: history, romance, travelogue, memoir, action, parody, politics, humor, and current events. Covering all that ground *could* make for a confusing literary experience, but it doesn't. The novel has added entertainment value for readers familiar with Rosenstone's real life, who may understand it as a roman a clef: after all, is it Redstone or Rosenstone? TJ or Warren Beatty? *Red Star in Madrid* or *Reds*? *Crusade in Spain* or *Crusade of the Left*? True life or not, it doesn't really matter, because a good read is a good read, and *Red Star, Crescent Moon* is certainly that. Readers may think they know where the plot is headed, but with Rosenstone as their tour guide, the trip is still great fun. *—PD* E&S

We've all heard of extreme sports and even extreme tourism (Chernobyl, anyone?), and we've all seen the adjective applied to specific phenomena and situations—extreme heat, extreme cold, extreme heights . . . you name it.

Well, how about extreme *places*?

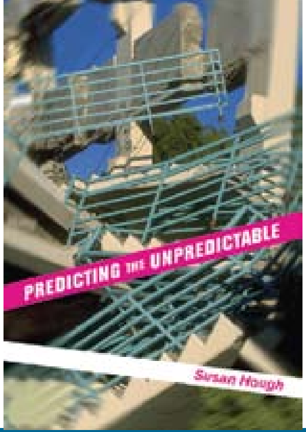
Have David Baker and Todd Ratcliff got a list for you. Not satisfied with our home world, they've put together a handbook that is part science guide and part Baedeker for the entire solar system.

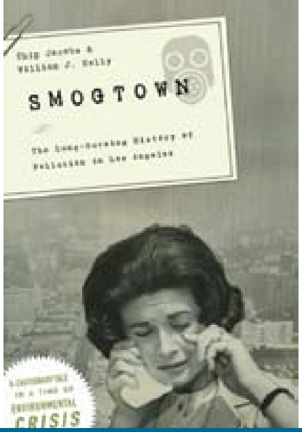
And a beautiful piece of work it is: *The 50 Most Extreme Places in Our Solar System* combines the gorgeous, and gorgeously reproduced, illustrations and photography of a coffee-table book—225 color, 25 halftones—with text as entertaining as it is informative, all packaged in a 7-by-8-inch, 304-page volume that can easily be carried around and—what a concept!—actually *read*.

Baker, chairman of the physics department at Austin College, and Ratcliff, a planetary geophysicist at JPL, have walked a very fine line—successfully overall—between accessibility without wandering into oversimplification on the one hand, and meaningful substance without lapsing into jargon on the other. Their text does require a certain level of sophistication and vocabulary—on a par with *Discover* magazine, say, or perhaps *E&S*—but they provide a comprehensive glossary at the back of the book.

Still, they occasionally undercut themselves, as when they remark in regard to a solar flare's direct hit on Earth in 1859, ". . . as you know, extreme things happen when magnetic fields connect." While that seems obvious once it's pointed out, the condescending tone is somewhat off-

Predicting the Unpredictable: The Tumultuous Science of Earthquake Prediction
by Susan Hough
Princeton University Press, 2010
272 pages, $24.95





Smogtown
by Chip Jacobs and William J. Kelly
The Overlook Press
2008
384 pages, $26.95

putting to the lay reader, at whom the book is clearly aimed.

One of the best features of the book—its spine, as it were—is the way Baker and Ratcliff keep returning to Earth. An introduction to Olympus Mons, the titanic martian volcano, provides an approach to discussing plate tectonics on Earth and the lack of them on Mars. Jupiter's Great Red Spot provides a lead-in to a chapter about earthly hurricanes.

Indeed, several chapters are devoted to Earth, which, among other assets, has the best surfing in the solar system (save perhaps for the truly mountainous waves suspected to occur on the lakes of Titan), as well as that so-far unique phenomenon—life.

Even when they have rambled off to the farthest reaches—the realm of rings, asteroids, comets, and the Oort Cloud—Baker and Ratcliff manage to work their way back to our mother world with a chapter on how Earth's moon was born.

The icing on the cake of this delectable work is the smorgasbord of facts at your fingertips. The chapter on martian dust devils, for example, reveals that the long lives of the Spirit and Opportunity rovers have been made possible by the periodic vacuuming of their solar panels by those swirling winds.

The chapters are in the four-to-five-page range, making this a work that can be nibbled occasionally as readily as it can be swallowed whole.

Finally, the book concludes with that increasingly rare phenomenon: an index that is genuinely useful.

Highly recommended, and worthy of a place beneath the Yule tree.
—*MF* E&S

The magnitude 7.0 Haicheng earthquake that hit northern China in 1975 killed 2,000 people. But the death toll was relatively small—the 7.5 Tangshan quake that struck the following year killed 250,000. Chinese officials proclaimed that thousands of lives were saved because they successfully predicted the tremor. A closer analysis reveals that seismologists and officials did anticipate the quake, but whether it was a true prediction, in which they knew exactly where and when the quake would happen, is a trickier question to answer.

In *Predicting the Unpredictable: The Tumultuous Science of Earthquake Prediction*, Susan Hough, a seismologist with the USGS in Pasadena, provides an insider's look at the science—and pseudoscience—of earthquake prediction. Hough takes the reader from the heyday of the field in the 1970s, when experts claimed accurate predictions were just around the corner, to the present day, when some are skeptical that predictions will ever be possible.

Hough's highly readable book is an insightful account of the scientific method, uncovering the often messy process behind the pursuit of truth. Science demands rigor, and seismology is no exception, as Hough describes ideas that both survive and fail upon close scrutiny.

Although scientists have made remarkable progress in understanding earthquakes over the last 50 years, predicting earthquakes is still really hard, if not impossible. So when we complain about seismologists' seemingly general warnings that an earthquake may happen tomorrow or 50 years from now, maybe we should give them a break. —*MW* E&S

On July 8, 1943, a thick blanket of gray mist engulfed Los Angeles, burning eyes and searing throats. The gaseous assault was so sudden that some thought the Japanese were beginning an invasion with chemical weapons. But the suffocating pall wasn't foreign—it was smog. And so begins *Smogtown*, by Chip Jacobs and William J. Kelly, a history of the fight against air pollution in Southern California.

The authors deliver a blow-by-blow account of subsequent struggles to find the source of the smog and return to Los Angeles the clear blue skies that had drawn so many westward in the first place. The themes and characters are all too familiar: relentless economic growth versus the environment and health; timid politicians or, worse, political leaders who fail to recognize the magnitude of the problem; businesses and industries that care only about the bottom line; a public reluctant to sacrifice an unsustainable lifestyle; and the regulatory agencies caught in between.

The primary players include Caltech's own Arnold Beckman (PhD '28) and Arie J. Haagen-Smit, a chemistry professor from 1937 until his retirement in 1971. As a science advisor to the city, Beckman recruited Haagen-Smit, now considered the father of smog control, to figure out the smog's underlying chemistry. Haagen-Smit determined that hydrocarbons, spewed out by cars and factories, react with nitrogen oxides in the air and form ozone, one of the principal components of smog. (See Haagen-Smit's article in the December 1950 issue of *E&S*.)

Beckman's leadership and advocacy, backed by Haagen-Smit's

Caltech Employees Federal Credit Union has surpassed $1 billion in assets — a milestone that the entire membership, as co-owners, can be proud of. But size alone is just a number. Our real pride involves the trust that this number reflects.

We realize that without member confidence in our safety and security, reaching this milestone would have been impossible. And so, we continue to strive to earn that trust, year after year…even through the recent challenging times in the economy.

So, when we celebrate the fact that we are now $1 billion strong, we are really celebrating the trust of our membership, the superior value of our selected financial products, and the simple integrity of every product and service we offer.

Our goal, in all of this, is to be YOUR **FIRST CHOICE** FOR SAFETY AND SECURITY. Beyond the added dimension of strength and stability, reaching $1 billion in assets tells us that we are reaching this goal.

CALTECH EMPLOYEES Federal Credit Union

800.592.3328 • www.cefcu.org

YOUR **FIRST CHOICE** FOR FINANCIAL SERVICES

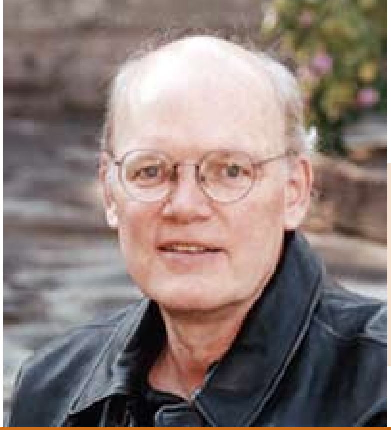
Foothill Office: 528 Foothill Blvd. • La Cañada Flintridge
JPL Office: 4800 Oak Grove Dr., Bldg. 218 • Pasadena
Campus Office: 515 S. Wilson Ave. • Pasadena

Must qualify for CEFCU membership to join. Minimum $5 deposit and 25¢ membership fee due upon opening any CEFCU account. All loans subject to credit approval. CEFCU is an Equal Opportunity Lender.

NCUA

Expect only the best from the Credit Union exclusively serving the extended Caltech & JPL community:

- *Vehicle Loans*
- *Visa Card*
- *Home Mortgages*
- *Home Equity Lines of Credit*
- *Personal Loans*
- *Online Currency Exchange*



For remembrances and information on memorial services and gifts, go to http://www.cds.caltech.edu/~marsden/remembrances/.

research, led to stricter regulations targeting hydrocarbon burning. Thanks to their work and the efforts of many others, the L.A. basin now has much cleaner air and bluer skies, even though the population has more than tripled since 1940.

But above all, the book is a cautionary tale. It's taken more than 60 years of political battles and, to a lesser degree, scientific research to achieve the relatively clean air we have. The authors warn that the same story is repeating itself—but now with greenhouse gases, whose short-term impact is much less immediate and tangible than the effects of that toxic haze of 1943. In the end, they argue, the only solution to the problems of climate change is to revamp our values and lifestyles. The question, then, is whether we can learn from history—or whether we're doomed to repeat it. —*MW* e&s

JERROLD E. MARSDEN

1942–2010

Jerrold Eldon Marsden, the Braun Professor of Engineering, Control and Dynamical Systems, and Applied and Computational Mathematics, passed away on the evening of September 21, 2010, with his wife and daughter by his side. He was 68.

Marsden was one of the leading world experts in mathematical and theoretical mechanics. His work spanned a variety of fields, including fluid mechanics, geometric mechanics, elasticity, control theory, dynamical systems, and numerical methods. By focusing on geometric foundations, he was able to unite different disciplines, connecting mathematical theory with physical models and practical applications. His work has, consequently, influenced geometers and physicists alike. His research has led to advances in many areas, including spacecraft mission design, turbulence modeling, and the design of underwater vehicles. Marsden's influence was felt around the globe, in no small part because of his countless international collaborations.

Born in British Columbia, Marsden graduated from the University of Toronto in 1965 with a BSc in mathematics. He received his PhD in applied mathematics in 1968 from Princeton. He then joined the faculty at UC Berkeley before coming to Caltech in 1992 as a Fairchild Distinguished Scholar. He was appointed professor of control and dynamical systems in 1995, and in 2003, he was named the Braun Professor. In 1992, he helped found the Fields Institute, a mathematical research institute at the University of Toronto, where he was a director until 1994.

Marsden was an accomplished educator and mentor, having written six undergraduate math textbooks, which are used worldwide, and 14 monographs, many of which are the definitive references in their fields. He has had more than 40 PhD students and postdocs. In 2006, Caltech's Graduate Student Council awarded him its Teaching and Mentoring Award.

He received numerous other awards that recognized his contributions as a researcher and educator: the Jeffrey-Williams Prize, the AMS-SIAM Norbert Wiener Prize, two Humboldt Prizes, a Fairchild Fellowship, the Max Planck Research Award, the SIAM von Neumann Prize, and the United Technologies Research Award. In 2006, he received an honorary doctorate from the University of Surrey. He was posthumously awarded the 2010 Thomas K. Caughey Award in November in Vancouver.

He was elected a Foreign Member of the Royal Society in 2006 and was a fellow of the Royal Society of Canada and the American Academy of Arts and Sciences.

He is survived by his wife, Barbara; his children, Christopher and Alison; grandchildren Eliza and Isaac; and a sister, Judy.

The family has requested that, in lieu of flowers, contributions be made to the Jerrold E. Marsden Scholarship Fund. Alternatively, contributions can be made to the Pasadena dog rescue, Mutts and Moms. A memorial service is planned for January 28, 2011. —*MW/JW* e&s

TEDx Caltech

Feynman's Vision: *The Next 50 Years*

14 January 2011

x = independently organized TED event

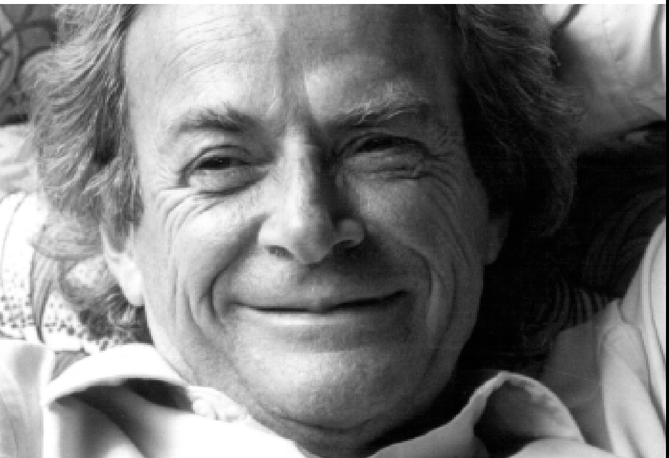
There's Plenty of Room . . .
but not for long!

Sign up TODAY!

TEDxCaltech is an unprecedented event that will bring together innovators, explorers, teachers, and learners for an exhilarating day of collaboration, conversation, and celebration inspired by Caltech's own Richard Feynman—Nobel laureate, iconoclast, and visionary.

The day will be an exciting and entertaining intellectual adventure!

Seats are limited! Sign up now:
TEDxCaltech.com



RALPH W. KAVANAGH

1924–2010

Ralph W. Kavanagh (PhD '56), professor of physics, emeritus, passed away on August 16 in Pasadena, California. He was 86.

Kavanagh was an expert in nuclear physics, primarily focusing on nuclear energy generation within the sun. As a member of Caltech's Kellogg Radiation Laboratory, he performed experiments looking at the fundamental interactions of light nuclei. He helped test some of the first models of evolving stars, which were based on his efforts to measure nuclear reactions thought to occur in the core of the sun.

Kavanagh focused on the steps in the chain that lead to the production of beryllium-7 and ultimately to the emission of neutrinos, the only particles that can escape unscathed from the center of the sun. These neutrinos carry information about the solar interior and detecting them has become an active branch of astrophysics. Kavanagh played a prominent role in this subfield through his careful studies of the properties of chlorine-37 and argon-37, the two nuclei involved in the detection of solar neutrinos that reach the earth.

In addition to the usual handful of graduate students he mentored, Kavanagh also taught the Advanced Physics Lab, beginning in the early 1970s and continuing until his retirement in 2000. This two-term course was required of all seniors majoring in physics; the few students committed to a theoretical career were permitted to substitute a thesis instead. In this lab, Kavanagh followed the pattern established by Caltech physicist Victor Neher (PhD '31), with all exams being a private oral grilling at the conclusion of each experiment. In this fashion, Kavanagh came to know his physics students well and served them as a graduate-school advisor.

Born in 1924 in Seattle, Washington, Kavanagh served in the U.S. Navy from 1942 to 1946 before receiving his BA from Oregon's Reed College in 1950, followed by his MA from the University of Oregon. Upon receiving his PhD, he continued at Caltech as a research fellow from 1956 to 1958, eventually becoming full professor in 1970. He became emeritus in 2000.

He was a fellow of the American Physical Society and the American Association for the Advancement of Science.

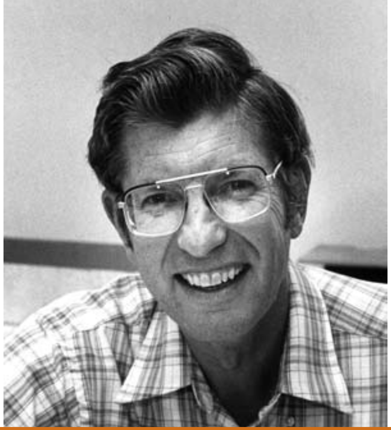
Outside the classroom, Kavanagh was an ardent classical pianist who was also fond of playing Ping-Pong. He enjoyed sailing and completing crossword puzzles, which he often could do in his head. An avid outdoorsman, he enjoyed camping and hiking.

His family says he will be remembered for his sharp wit and wry sense of humor, for his high standard of ethics and his compassion for those less fortunate, and for his love of nature.

"Above all, science was not only his career, but his passion and hobby," says his wife, Joyce.

He is also survived by daughters Kathleen Kavanagh, Janet Kavanagh, Stephanie Kavanagh Harlan, and Linda Kavanagh; eight grandchildren; and one great-grandson. His son, William Kavanagh, predeceased him.

—*JW* E&S



THAD VREELAND, JR.

1924–2010

Thad Vreeland Jr., professor of materials science, emeritus, passed away August 9 in San Gabriel, California. He was 85 years old.

Vreeland—a member of Caltech's materials science program from its earliest days—was best known for his studies of the mechanical properties of materials, with an emphasis on how severely stressed materials deform plastically and permanently.

"His specialty was defects in materials—specifically dislocations, which are the agents of plastic deformation," says Brent Fultz, professor of materials science and applied physics, and one of Vreeland's colleagues.

In the 1960s and '70s, Fultz says, Vreeland performed challenging experiments to measure how fast dislocations move in metal crystals; in the '80s, he studied how defects in thin layers of semiconductor materials are generated by ion bombardment or stresses. Vreeland's work in the 1990s included studies of how powders can be consolidated into bulk materials by subjecting them to strong mechanical shocks.

"Thad Vreeland took pride in laboratory technique and had both skill and style in building his own equipment, often frugally," says Fultz. "With his graduate student David Pope [MS '62, PhD '67], he designed and built a device for subjecting large crystals to pulsed torsional loads, and he built several X-ray diffractometers of unique design. Thad Vreeland's shock-wave consolidation facility used the barrel of a field gun that he reinforced for even higher velocities."

Vreeland worked as a consultant for organizations such as Union Carbide, and collaborated on varied materials projects with corporations and research institutions such as the McDonnell Douglas Research Laboratory.

In 1965, Vreeland coauthored *The Analysis of Stress and Deformation* with engineering professor George W. Housner (MS '34, PhD '41), who passed away in 2008.

Vreeland was born in 1924 and was a lifelong member of the Caltech community, receiving his BS in 1949, his MS in 1950, and his PhD in 1952. That same year, he was named a research fellow in engineering; he subsequently joined the Caltech faculty in 1954 as an assistant professor of mechanical engineering. Vreeland was a professor of materials science from 1968 until his retirement in 1991, whereupon he was named professor emeritus.

After his retirement, Vreeland spent a great deal of time in his Montana home—most of which he designed himself, says his wife, Mary Vreeland. "It was near West Yellowstone, which is the trout fishing center of the west," she adds. "Lots of Caltech faculty and students came up to fish with him."

In addition to Mary, Vreeland is survived by his children—Michael, Terry, and Janet—and two grandchildren, Theresa and Johanna. —*LO* E&S

المعهد البترولي
THE PETROLEUM INSTITUTE

أدنوك
ADNOC
شركة بترول ابوظبي الوطنية

ADNOC PI Research Center (ADPIRC)

The ADNOC Research Centre at the Petroleum Institute is seeking applicants for the following positions:

- Liaison Project Manager
- Senior Building Management and Maintenance Engineer
- Senior Laboratory Specialist
- Senior Safety and Environmental Engineer

The **ADNOC Research Centre at the Petroleum Institute (ADPIRC)** in Abu Dhabi is dedicated for the advancement of science, technology and local capabilities to address the needs of the petroleum industry in UAE and the region. This Centre will house world-class academics, scientists and industry partners working together on cutting edge research in various interdisciplinary research in petroleum geosciences and engineering, in chemical, mechanical, and electrical engineering and in applied sciences. Through the collaboration of ADNOC group of companies, international share holders, energy service providers and industrial corporations, innovations and technology advancement will progress quickly from basic research and development to commercialization in the marketplace. The center is currently in the design phase and is expected to be completed by mid of 2012.

Salary/Benefits: The total compensation package includes a tax-free 12-month base salary, and a benefits allowance that covers relocation, housing, initial furnishings, utilities; transportation (automobile purchase loan), health insurance, end-of-service benefit and annual leave travel. Applicants must be in excellent health and will be required to pass a pre-employment physical examination.

The Petroleum Institute (PI) was created in 2001 with the goal of establishing itself as a world-class institution in engineering education and research in areas of significance to the oil and gas and the broader energy industries. The PI's sponsors and affiliates include Abu Dhabi National Oil Company and several major international oil companies, namely Shell, BP, Jodco and Total. The campus has modern instructional laboratories and classroom facilities and is now in the planning phase of three major research centers on its campus. The PI is affiliated with the Colorado School of Mines, the University of Maryland (College Park), the University of Minnesota and Johannes Kepler University in Linz, Austria. Recent additions to collaborating institutions include Rice University and University of Texas, Austin. The growth of the PI is instrumental to meet the business and research needs of the fast growth of the UAE industry. For additional information, please refer to the PI website: **www.pi.ac.ae.**

For more information on the positions, please visit the following website and apply online:

http://www.pi.ac.ae/jobs/ADPIRC

Review of applications will begin immediately and will continue until successful candidates are selected. Only short-listed applicants will be notified.

Help Caltech do something it does best: groundbreaking research

In the lab of Bowles Professor of Chemistry Brian Stoltz, grad students like Allen Hong (pictured) are engaging in research that could ultimately lead to potent new disease-fighting drugs.

Establish a lifetime income today and provide support for the critical research needs of tomorrow.

Financial support is crucial to Caltech's ongoing success as the costs of pioneering research increase. Trusts and bequests provide a solid foundation for the important work underway at the Institute. By establishing a charitable trust, you can receive a charitable deduction and a supplemental income stream for yourself and/or a loved one while building a lasting legacy.

Contact Caltech's Office of Gift Planning to develop a personalized plan that reflects your financial goals and philanthropic wishes.

(626) 395-2927
giftplanning@dar.caltech.edu
www.giving.caltech.edu/gp

California Institute of Technology 1891

Office of Gift Planning

IF A MATHEMATICAL EQUATION COULD EXPRESS GRATITUDE, WE'D USE IT.

We're TIAA-CREF, and we've been a trusted partner of Caltech since 1920. Now, we're honored to be their single administrative services provider for retirement planning as we continue to offer personalized, objective advice with a long-term commitment to their financial goals.* For over 90 years, we've helped millions of people in the academic, medical, cultural, and research fields live well in retirement.

Join us, and make a change for the good. Call to discuss your portfolio at 888 556-2451 or visit us at tiaa-cref.org/hereforyou. For a personalized counseling session, schedule an appointment at our local office.

2 North Lake Avenue, Suite 150, Pasadena
800 732-8353

TIAA CREF

FINANCIAL SERVICES FOR THE GREATER GOOD®

*Our advisors receive no commissions. TIAA-CREF compensates the advisors through a salary-plus-incentive program based on client service excellence and financial results. Advisors will only recommend products that help achieve our clients' goals. **TIAA-CREF products may be subject to market and other risk factors. See the applicable product literature, or visit tiaa-cref.org for details.** Before transferring assets, consider the differences in features, costs, surrender charges, services, company strength and any tax consequences. C46514 © 2010 Teachers Insurance and Annuity Association-College Retirement Equities Fund (TIAA-CREF), 730 Third Avenue, New York, NY 10017. TIAA-CREF Individual & Institutional Services, LLC, and Teachers Personal Investors Services, Inc., members FINRA, distribute securities products. Annuity contracts and certificates are issued by Teachers Insurance and Annuity Association (TIAA) and College Retirement Equities Fund (CREF), New York, NY.

Consider the investment objectives, risks, charges and expenses carefully before investing. Visit tiaa-cref.org for a prospectus that contains this and other information. Read carefully before investing.

e&S

Engineering & Science

California Institute of Technology
Pasadena, California 91125