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Engineering & Science

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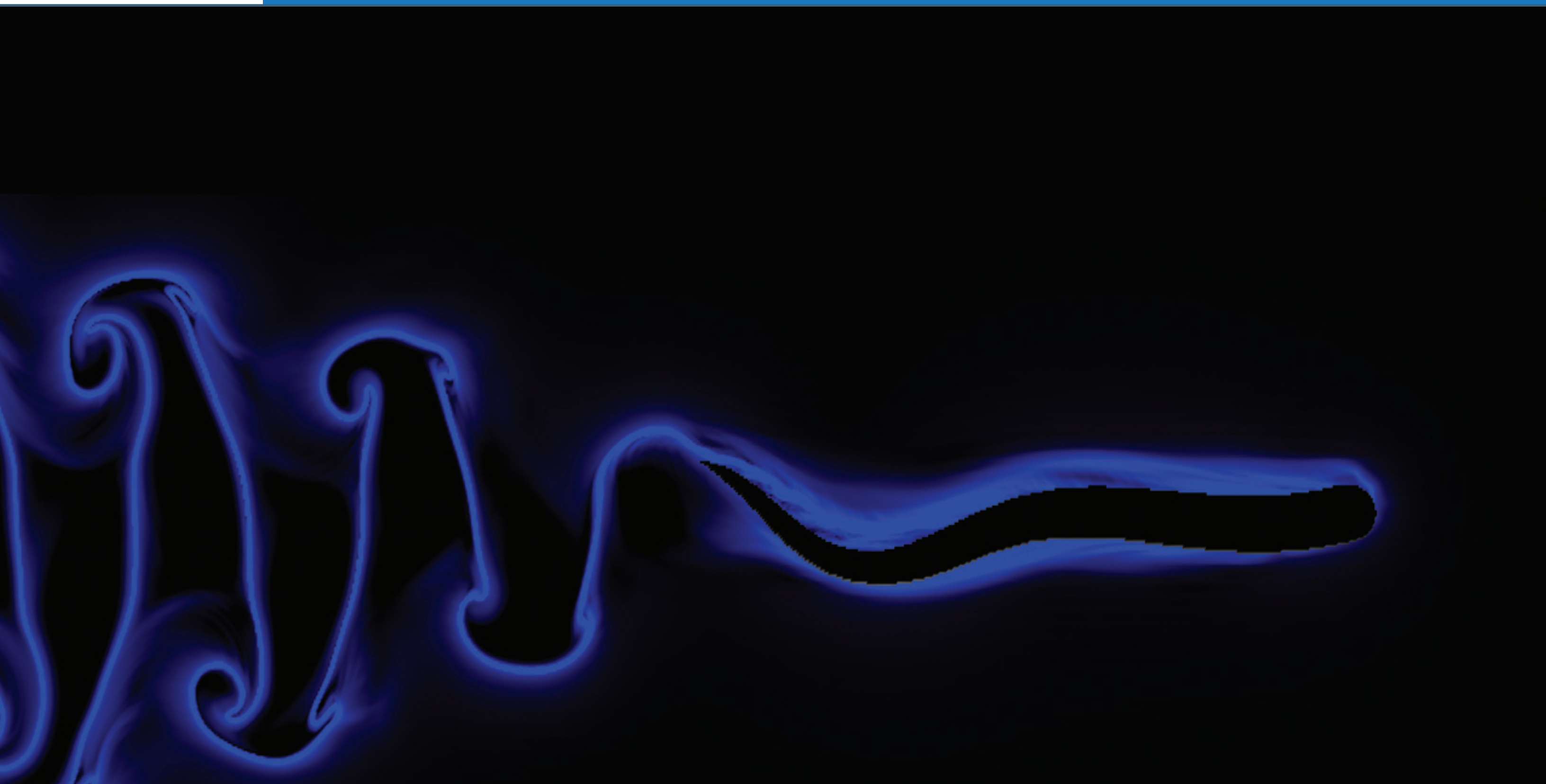
VOLUME LXXIII, NUMBER 3, SUMMER 2010

California Institute of Technology

ON THE COVER
The dome of the 200-inch Hale Telescope on Palomar Mountain on a summer evening. Just to the left of the dome, you can see the center of the Milky Way.

AN EEL'S WAKE



A simulated eel swims by, leaving behind its wake. The blue wisps represent Lagrangian coherent structures, which are boundaries that separate different types of flow. In this case, the structures divide the swirling vortices from the rest of the fluid. These structures are important not only in understanding how sea creatures propel themselves, but also in understanding other fluid systems, such as how air flows around planes and how pollution spreads in the ocean. Clara O'Farrell, a graduate student working with Associate Professor of Aeronautics and Bioengineering John Dabiri (MS '03, PhD '05), made this image based on a simulation done by Stefan Kern and Petros Koumoutsakos from the Swiss Federal Institute of Technology in Zürich (ETH Zürich). This image is part of Caltech's 2010 Art of Science exhibit. To see more submissions, go to www.artofscience.caltech.edu.

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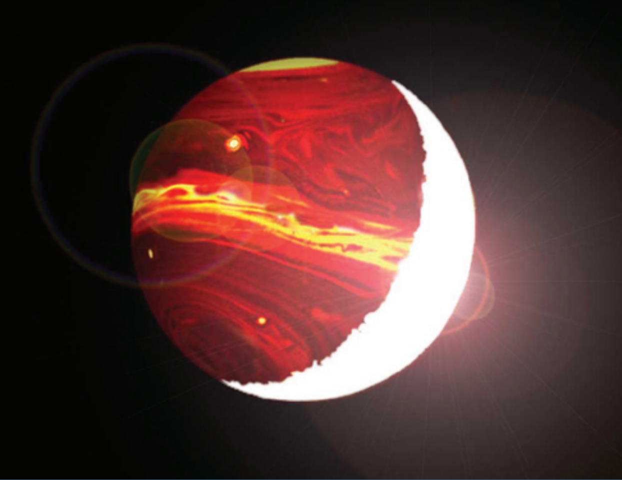

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Engineering & Science (ISSN 0013-7812) is published quarterly at the California Institute of Technology, 1200 East California Boulevard, Pasadena, CA 91125. Annual subscription $20.00 domestic, $30.00 foreign air mail; single copies $5.00. Send subscriptions to Caltech 1-71, Pasadena, CA 91125. Third-class postage paid at Pasadena, CA. Published by Caltech and the Alumni Association. Telephone: 626-395-3630.

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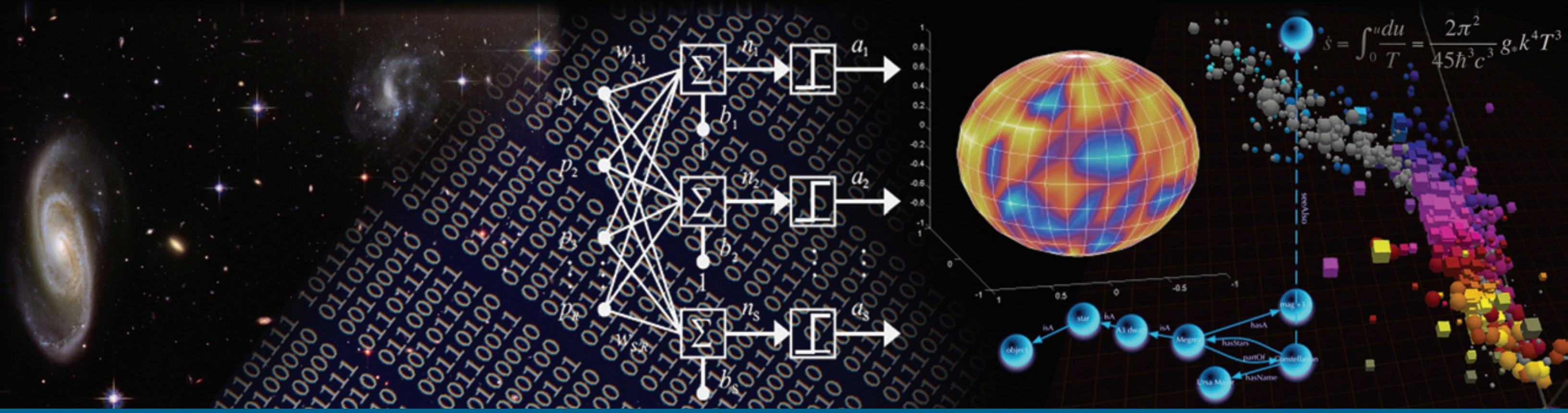
Cover, 18, 23, 26, 28, 29 — Bill Youngblood; inside front cover — Clara O'Farrell; 5 — Lavochkin Association, NASA/GSFC/Arizona State University; 6 — ESA 2010 MPS for OSIRIS Team, MPS/UPD/LAM/IAA/RSSD/INTA/UPM/DASP/IDA; 7, 31 — NASA/JPL-Caltech; 8, 35 — Bob Paz; 10 — Mark Bigelow; 11 — Doug Cummings; 12, 14, 16, 17 — David MacKay; 13 — SunPower, Abengoa Solar; 14 — Eco-Cute, still from Terminator 2: Judgment Day courtesy of StudioCanal, David Faiman, General Motors; 19 — ESO/L. Calçada; 21 — NASA/ESA/G. Bacon (STScI); 23 — Greg Laughlin; 24 — Wolfe Gleitsman; 31 — Frances Arnold; 32 — Jim Sturm, Paul Richards; 33, 34 — Brendan Crill; 33 — Eric Hivon and Phil Mauskopf; 35 — Jamie Bock and Anthony Turner, JPL



A UNIVERSE OF ASTRONOMICAL DATA

Long gone are the days of the lone astronomer perched atop a mountain, peering through an eyepiece at a smudge in the night sky. Modern astronomers, though, still have to go out and get their own data, either spending nights in the telescope's control room or observing remotely.

But for the astronomer of 2020, data will automatically come to her before she wakes up in the morning. While she sleeps, telescopes on autopilot will comb the night sky, feeding many terabytes (a thousand billion bytes) of data into computers. The computers will then mine the data, flagging any intriguing cosmic events, such as new supernovae or explosive gamma-ray bursts, for our astronomer to peruse while sipping her morning brew. Computers will also have collected information from other databases that may be relevant—multiwavelength images of that part of the sky, for example.

> "We'll be able to ask questions that we couldn't dream of asking before," says George Djorgovski.

Later, she might log onto some three-dimensional virtual environment, where virtual representations of herself and astronomers from around the globe will literally immerse themselves in the data—a colorful three-dimensional cluster of spheres that represent the hundreds of characteristics that describe, for instance, a supernova—analyzing the supernova in ways that would have been inconceivable a mere 10 years earlier.

Welcome to astroinformatics—an amalgam of astronomy and computer science. Increasingly powerful instruments, more sensitive telescopes, and ever-faster computers are inundating the astronomical community with far more data than it ever imagined. The next generation of sky surveys is expected to uncover billions of stars and galaxies and lots of other interesting things, such as supernovae, quasars, exoplanets, and possibly new objects that have yet to be discovered—each with hundreds of parameters.

The Large Synoptic Survey Telescope project, of which Caltech is a partner institution, will produce petabytes of data—roughly the amount of information contained in a billion books. Another project planned for the future, the Square Kilometre Array, is expected to yield *exa*bytes of data—a billion billion bytes. By comparison, Caltech's been involved with numerous surveys—such as the Digitized Palomar Sky Survey, Palomar-Quest, the Palomar Transient Factory, and the Two-Micron All Sky Survey—that have generated tens of terabytes of data, a factor of at least a thousand less than what future surveys will produce. And the size of data will follow Moore's Law, doubling every couple of years.

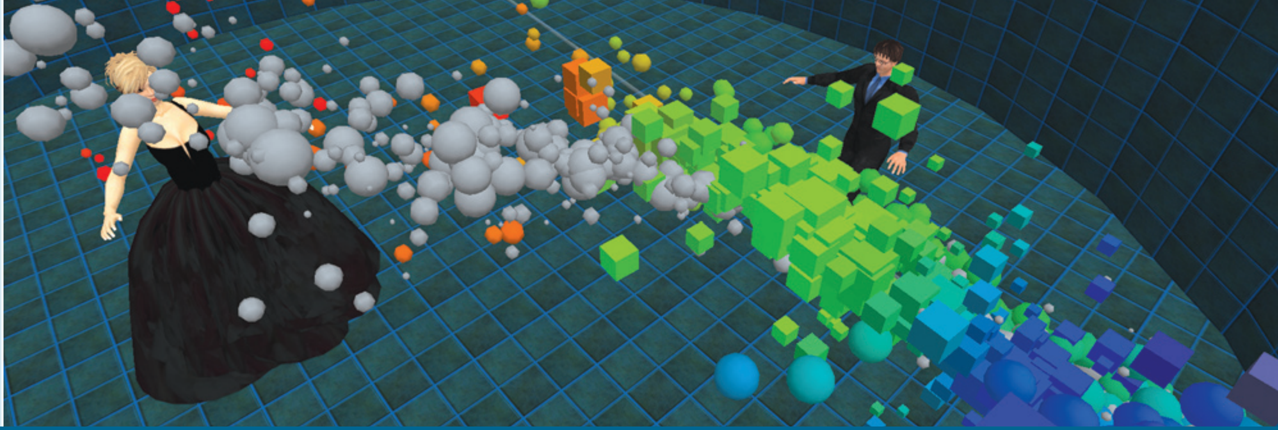
It's not just that the databases will be huge. They'll be complex—imagine trying to visualize, much less understand, hundreds parameters all at once. Sifting through the numbers is humanly impossible, so Caltech astronomers are taking the lead in developing tools to process, analyze, and understand this deluge of information.

For example, the so-called Virtual Observatory (VO), which Caltech has been a leader in developing since its inception 10 years ago, is a way to integrate all the data that's being collected by telescopes from around the world and in orbit. Every telescope's data sets are different, not only in terms of what information is gathered—Chandra is a space telescope that looks at X-rays, and Keck is an optical scope on top of Mauna Kea, for example—but also in format and how they're accessed. But with the VO, an astronomer can enter a query on the computer and get to all the relevant databases at once, without having to learn the quirks and technicalities that accompany each data set. "Federating is the word that's normally used for this," says Matthew Graham, a computational scientist at Caltech's Center for Advanced Computing Research (CACR). "You're federating these different data sets and then using online services to do things with them."

After a decade of developing the tools and infrastructure needed to get these databases to talk to each other, the project, now called the Virtual Astronomical Observatory and funded by NASA and the NSF, opened for business in May. "We're moving onto the operational phase," says Graham, a member of the program council of the VAO. "The hope is that we can

Left: The exponential rise in information is changing how astronomy is done.

Right: This image from Second Life shows two avatars immersed in a virtual world of three-dimensional data.



really make an impact on the community." In addition to Graham, CACR computational scientist Roy Williams (PhD '83) also plays a leading role with the VAO. Others at Caltech who are involved with astroinformatics include CACR executive director Mark Stalzer, CACR computational scientist Andrew Drake, executive director of the Infrared Processing and Analysis Center (IPAC) George Helou, IPAC scientists Joe Mazzarella and Bruce Berriman, postdoc Ciro Donalek, staff scientist Ashish Mahabal, and others.

But there's more to astroinformatics than just bigger telescopes, better computers, and more sophisticated software. "It's not just the same old stuff with more data, but genuinely new things," says George Djorgovski, professor of astronomy and principal investigator for Caltech's part of the VAO consortium. "We'll be able to ask questions that we couldn't dream of asking before, just because we didn't have the tools or the data." This past June, Djorgovski was one of the organizers of the first astroinformatics conference, held at Caltech's Cahill Center for Astronomy and Astrophysics and attracting about a hundred astronomers from around the world. Participants spent four days discussing a wide array of topics, ranging from data mining and computation to education and outreach. The conference was even broadcast live on the Web, and participants posted comments on Twitter during the talks.

The outreach goes far beyond education, as astronomers are actually soliciting the public's help. You're probably familiar with SETI@home, a program that uses your computer's downtime to search radio-telescope data for signs of extraterrestrial life. Astronomers want to take advantage of your brain, as well as your laptop. Galaxy Zoo, for example, is a website that asks users to classify thousands of individual galaxies from the Sloan Survey. Distinguishing a spiral galaxy from an elliptical one is a complex problem for a computer, but a simple one for a human. With more than 250,000 users, Galaxy Zoo has spawned similar projects to help astronomers sift through data taken by other missions, like the Lunar Reconnaissance Orbiter and the Hubble Space Telescope.

But even turning the entire world into an astronomy sweatshop will fall short. "There aren't enough humans on the planet to handle the data right now," Graham says. So researchers like him want to take this idea of "citizen astronomy" farther and figure out how citizen scientists interpret data to develop smarter data-mining algorithms. For instance, a human can identify a bright light in the spiral arm of a galaxy as a supernova, because we know that an exploding star has to live in a galaxy. Understanding this kind of contextual information is hard for a computer, but if machine-learning researchers analyze enough images in which supernovae have been spotted by humans, then some other characteristics that a computer can process may be uncovered.

This sort of technique, part of a subfield called semantic astronomy, is still in its early stages, Graham says. But a lot of astroinformatics will involve similar tools that turn the computer from a number-crunching machine into an intelligent assistant. Instead of having to mine through different databases and pick out the relevant numbers by hand, an astronomer could just type in a query in plain English—for example, "find all the data on stars within 100 light-years of us"—and the computer would cull all the relevant information from every database available, leaving the astronomer free to focus on the science.

Of course, astronomy is far from being the only field overwhelmed with information. The burgeoning field of *bio*informatics has been transforming biology for the past decade. Other sciences are facing similar challenges: real-time sensors monitoring everything from earthquakes to climate are generating a barrage of data, and Moore's Law is driving an exponential growth in information. "Any science that's using semiconductors to do detection is suddenly becoming data-intensive," says CACR's Mark Stalzer.

"Science in the 21st century is going to be different," Djorgovski adds. "The focus is shifting from having better hardware to having better software and methodology. It's going from atoms to bits to knowledge." With the smart phones, social networking, and news feeds that inundate our everyday lives, we're all experiencing a torrent of information. And like the rest of us, astronomers are learning to deal with it. —*MW* e&s

If you want to learn more about astroinformatics, you can find slides and videos of all the talks from the Astroinformatics 2010 conference at www.astroinformatics2010.org.

TOLERATING A FETUS

Your immune system recognizes cells in your body that aren't yours, hunts them down, and kills them. So how does a fetus survive? Half of its genes and all of its tissues are unlike mom's, yet the body does not attack this invader.

Caltech biologists have discovered that a particular type of immune cell—produced in response to specific fetal antigens, proteins that stimulate the immune system—allows "pregnancy tolerance," as it's called.

"Our finding that specific T regulatory cells protect the mother is a step to learning how the mother avoids rejection of her fetus. This central biological mechanism is important for the health of both the fetus and the mother," says David Baltimore, the Millikan Professor of Biology, and recipient of the 1975 Nobel Prize in Physiology or Medicine.

Scientists had long been "hinting around at the idea that the mother's immune system makes tolerance possible," says Daniel Kahn, a visiting associate in biology at Caltech, and an assistant professor of maternal–fetal medicine at the UCLA. What they didn't have were the details of this tolerance—or proof that it was immune-related.

Now they do. Baltimore and Kahn selectively destroyed the T regulatory cells in a strain of mice bred so that all the males—including male fetuses—carry on their cells' surfaces a protein known as a "minor transplantation antigen." Female mice lack this antigen.

Normally, pregnancy tolerance would kick in and protect the male fetuses from any maternal repercussions.

So if the T regulatory cells provided the shield, their destruction would give the immune system free rein to go after the antigen-laden males—and only the males.

And indeed, fewer male fetuses survived to birth. Those that did were of significantly lower birthweight, presumably because of the inflammation caused by the mother's immune response to that single antigen.

The scientists found that pregnancy tolerance "develops actively as a consequence of pregnancy," says Kahn. "The mice are not born with it." Indeed, virgin mice showed no signs of these pregnancy-specific T regulatory cells. Conversely, the cells were found in larger numbers in mice that had given birth to male babies, with the level of T regulatory cells increasing with the number of male births.

The next step, Kahn adds, is to look at T regulatory cells and their role in pregnancy tolerance in humans—a line of research that may lead to insights into such pregnancy-related conditions as preeclampsia, in which high blood pressure and other symptoms develop in the second half of pregnancy. Preeclampsia is a major cause of maternal mortality around the world.

"There's a lot to be learned," he says. "Pregnancy is often ignored in research because it's usually successful, and because—from an immunologic standpoint—it has such complexity. Until now, it's been difficult to get a handle on how the immunology of pregnancy really works."

The work is described in an article by Baltimore and Kahn in the May 18 issue of the *Proceedings of the National Academy of Sciences*. The research was supported in part by a grant from the Skirball Foundation. *—LO* e&s

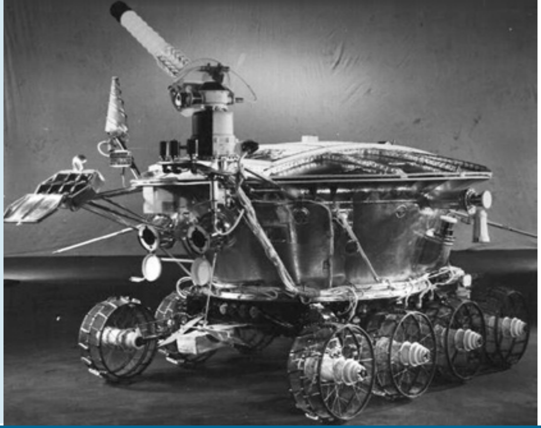
SHOOT THE MOON, HIT A ROVER

A Caltech alum has found a lunar rover that's been lost for 40 years. On November 17, 1970, Lunokhod 1 rolled off a ramp from the Russian spacecraft Luna 17 and became the first remote-controlled robot to land on another world. The eight-wheeled vehicle, about the size of a riding mower, explored Mare Imbrium, the Sea of Rains, covering 10.5 kilometers and traveling for 322 days before its handlers lost contact with it. The second Lunokhod (Russian for "moonwalker") landed on January 15, 1973, and covered 37 kilometers over four months before it overheated.

The twin Lunokhods had French-built laser reflectors on their backs, and since Lunokhod 2's exact location was known, scientists have been shooting laser pulses at it to measure the distance to the moon with extreme accuracy. On the other hand, Lunokhod 1's coordinates were known only to within five kilometers—to hit it with laser pulses, you would need to know where it is within better than 100 meters. "It's good enough to put a push-pin into a map, but not

Right: Looking kind of like a bathtub on wheels, the Lunokhod 1 is 2.3 meters long and 1.5 meters tall. The reflectors sit in the tray jutting out on the left.

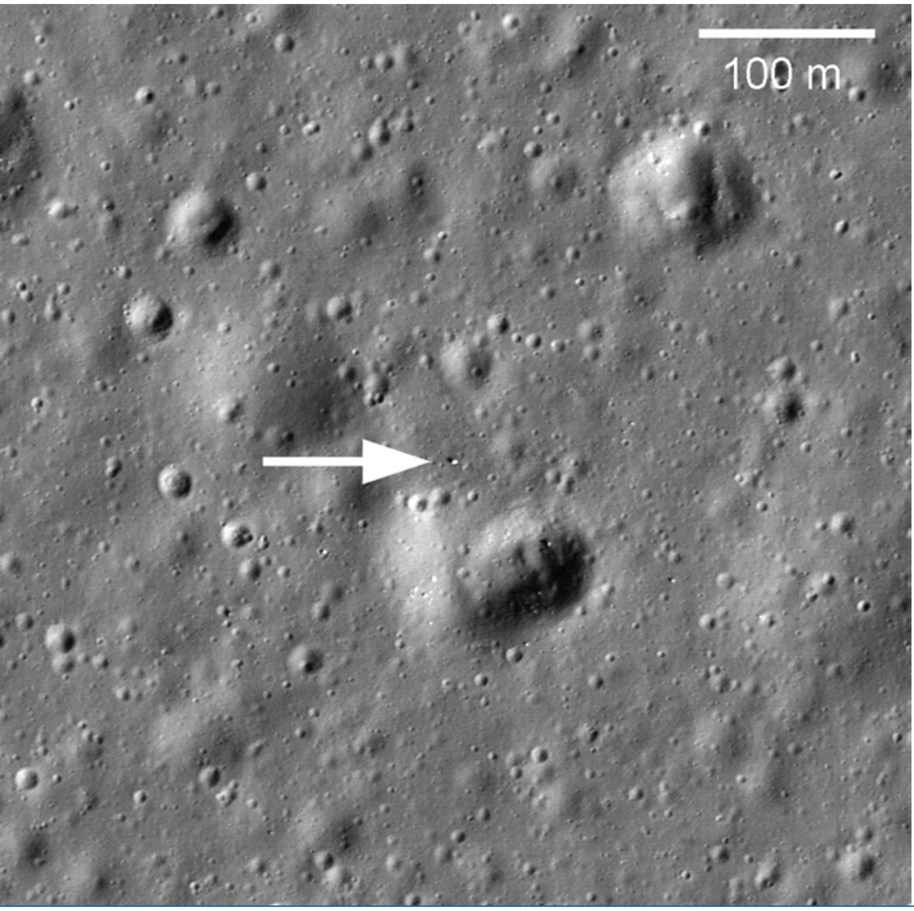
Below: The final location of the Lunokhod 1 rover.



nearly good enough to make a laser search likely to succeed," says Tom Murphy (MS '97, PhD '00), associate professor of physics at UC San Diego and the principal investigator for the Apache Point Observatory Lunar Laser-ranging Operation (APOLLO).

The project is recording every tilt, tip, and wobble of the moon in order to gauge its precise orbit and test Einstein's theory of gravity, general relativity. APOLLO uses the 3.5-meter telescope at the Apache Point Observatory in New Mexico to shoot lasers at the Lunokhod reflectors or one of the other three reflectors planted on the surface by Apollos 11, 14, and 15. By timing how long it takes the laser pulse to return to the telescope, researchers know exactly how far it is to that point on the moon's surface. Each reflector consists of an array of three mutually perpendicular mirror segments arranged like the inner corner of a cube. These so-called corner reflectors bounce the light beam directly back toward its source, regardless of its direction. Apollos 11 and 14 have 100 reflectors in their arrays, Apollo 15 has 300, and the Lunokhods have 14 larger ones.

Although they had four targets, Murphy and his colleagues wanted to find Lunokhod 1 because it sits nearer to the edge of the lunar disk. The moon's axial tilt and precession cause it to wobble, and the outer part of the disk—called the limb—moves the most toward or away from Earth, which is what laser ranging measures well. Figuring out the limb's motion would thus give a more accurate measurement of the total wobble. Since the team had a rough guess as to where Lunokhod 1 was, give or take five kilometers, they hoped to hit the rover's mirrors with laser pulses. The laser beam, which leaves the telescope about three meters wide, stretches to two kilometers by the time it hits the moon. Still, nothing ever came back. "It almost seemed like a waste of telescope time," Murphy says.



Meanwhile, NASA's Lunar Reconnaissance Orbiter (LRO) had been snapping shots, at a resolution of one meter, of all the lunar-landing sites, from those of Apollo to those of the Russian Luna missions. In March, LRO took a picture of the area around Luna 17's landing site, and spotted the missing rover. It was four kilometers from where Murphy and his team thought it was, and without LRO's help, they would've never had a chance to find it, he says. LRO was able to pinpoint the rover's coordinates to within 100 meters, giving APOLLO a target to work with.

Hitting a mirror with a reflective area of 489 square centimeters from 384,400 kilometers away is like trying to hit a grain of rice in New York City from Los Angeles. The researchers shoot 20 pulses per second, and with every pulse, they blast 10^{17} photons at the target. On a good night, maybe one photon per pulse bounces back and reaches the telescope. Because the signal is so weak, the detector has to amplify every photon it

FIRST STEPS FOR CURIOSITY

The Mars rover named Curiosity is taking shape. Engineers have installed its wheels and its remote sensing mast, which holds up the rover's set of cameras, forming its neck and head. On July 23, Curiosity took its first steps, slowly rolling across the floor at JPL. Watch a video of Curiosity's first test drive.

receives. As a result, it is only turned on for 100 nanoseconds per pulse, to avoid picking up background photons that would flood out the signal. Since light travels at almost 300,000,000 meters per second, this means the distance to Lunokhod 1 had to be known to within about 15 meters, although the team was later able to improve their technique and widen the window to 90 meters. Using LRO's altimeter, called LOLA, the researchers determined the elevation of the Sea of Rains to within five meters, and on April 22, when they started firing, photons came piling in—the first time any signal has come from Lunokhod 1 in four decades.

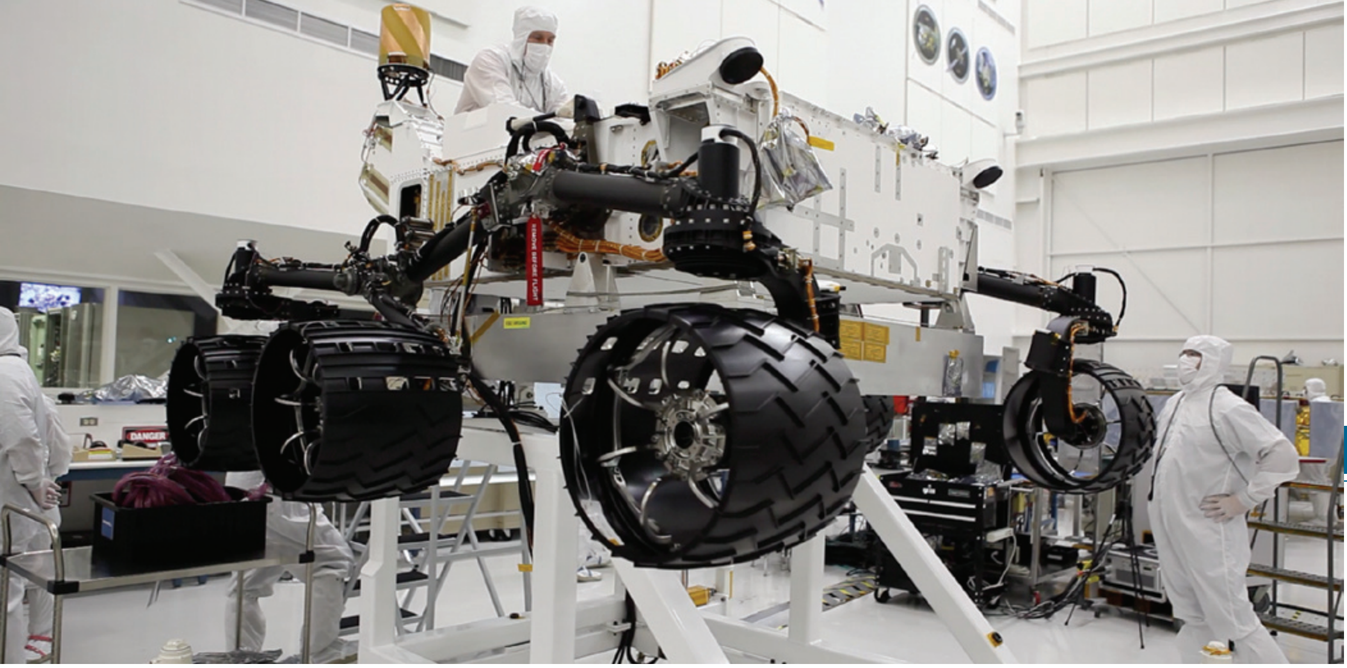
Lunokhod 1 was so reflective that it shocked Murphy and his team. After sending about 10,000 pulses, the team had gotten about 2,000 photons back—a bounty compared with the best-ever 750 photons that Lunokhod 2 had returned from 5,000 pulses. Overall, Lunokhod 1 is five times brighter than its twin. Since the Lunokhods are identical, and one would expect both mirrors to have endured similar degradation from dust and tiny meteorites, why the twin rovers are so different is a mystery.

The newfound rover also outshines the mirrors left by Apollo 11 and 14, making it the second brightest reflector on the moon. "Its position near the limb, combined with the fact that it's so strong, means that it will become, after Apollo 15, our most valuable target," Murphy says. APOLLO can measure distances to within a millimeter, and the team is now trying to pin down Lunokhod 1's location to that degree of accuracy. This will take about a year, after which they'll be able to get equally accurate numbers for how the moon wobbles, leading to a better fix on the center of the moon's mass and therefore the shape of its orbit. Isaac Newton's 300-year-old equations describe orbits quite well, but when you zoom in to a scale of around five meters, general relativity gives different numbers. APOLLO's data will test Einstein's theory to an accuracy of one part in 10,000.

Other than testing general relativity, knowing the precise motions of the moon will also help scientists glean details about the moon's interior structure and composition. "Imagine that you walk along a sidewalk and run into a trash can," Murphy explains. "If the can falls over, it's empty. If it wobbles, it's full of stuff." Scientists still don't know for sure whether the lunar core is entirely liquid or solid, or a combination of both, nor do they fully understand the interaction between the core and the mantle. Knowing more about lunar interior structure will tell us more about how the moon and solar system formed—and ultimately, how we all came to be. *—MW*

LUTETIA AND SATURN

Saturn hovers behind the asteroid Lutetia. The Rosetta spacecraft took this snapshot from 36,000 kilometers away with its OSIRIS narrow-angle camera. Operated by the European Space Agency, Rosetta will arrive at Comet 67P/Churyumov-Gerasimenko in 2014 and send a lander to explore the comet's surface. Researchers at JPL help with the American contribution to the mission, which includes three instruments: an ultraviolet imaging spectrometer called ALICE, a microwave instrument called MIRO, and an ion and electron sensor (IES).



T CELLS MAKE A COMMITMENT

When does a cell choose its particular identity? That's one of the big questions in biology. We now know the answer, at least for a branch of the immune system called T cells.

The activation of a gene called *Bcl11b* is a "clean, nearly perfect indicator of when cells have decided to go on the T-cell pathway," says Ellen Rothenberg, the Ruddock Professor of Biology at Caltech.

The *Bcl11b* gene acts to shut off other genes in the stem cells from which T cells are born, allowing the stem cells to pick one of the many developmental paths open to them.

"Stem cells and their multipotent descendents follow one set of growth rules, and T cells another," says Rothenberg, "so if T-cell precursors don't give up certain stem-cell functions, bad things happen."

The conversion from T-cell precursors to actual T cells takes place in the thymus, a specialized organ located near the heart. "When the future T cells move into the thymus," Rothenberg explains, "they are expressing a variety of genes that give them the option to become other cells," such as mast cells (which are involved in allergic reactions), killer cells (which kill cells infected by viruses), and antigen-presenting cells (which help T cells recognize targeted foreign cells).

As the T cells enter the thymus, the organ sends molecular signals to the cells, directing them down the T-cell pathway. At this point, the *Bcl11b* gene gets turned on, blocking other pathways. This is critical.

"For cells that never divide again, maintaining identity is trivial. What they are at that moment is what they are forever," Rothenberg says. But T cells keep dividing as they migrate around the body and interact with other types of cells.

The Bcl11b protein "is like a switch that allows the cells to shut off stem-cell genes and other regulatory genes," Rothenberg says. "It keeps them clean—and may be necessary to 'guard' the T cell from becoming some other type of cell."

Although it is thought that many genes are involved in the process of creating and maintaining T cells, "*Bcl11b* is the only regulatory gene in the whole genome to be turned on at this stage," she adds, "and it is probably always active in all T cells. It is the most T-cell specific of all of the regulatory factors discovered so far." Among blood cells, this gene is only expressed in T cells, she says. "The gene is used in other cells in completely different types of tissue, such as brain and skin and mammary tissue, but that's how the body works. There's no confusion, because something like brain tissue and mammary tissue will never be a T cell."

When *Bcl11b* is not present—as in mice genetically altered to lack the gene—T cells "don't turn out right," Rothenberg says. Indeed, T cells in some individuals with T-cell leukemia have been found to have lost the gene. "It may make them more susceptible to the effects of radiation, because the cells don't know when to stop growing," she says. "We think that the loss of one of the two copies of the gene is enough to prevent cells from growing appropriately."

The discovery is described in "An Early T Cell Lineage Commitment Checkpoint Dependent on the Transcription Factor *Bcl11b*," a paper in the July 2 issue of *Science*—one of three papers on the *Bcl11b* gene. The paper was coauthored by Rothenberg, Caltech postdoc Long Li, and Mark Leid of Oregon State University. The work was supported by the California Institute for Regenerative Medicine, the National Institutes of Health, the Caltech–City of Hope Biomedical Research Initiative, the Louis A. Garfinkle Memorial Laboratory Fund, and the Al Sherman Foundation. —*KS* e&s

Associate Professor of Aeronautics and Bioengineering John Dabiri, shown here with his jellyfish tanks, first became interested in studying the organism's propulsion system while doing a SURF project at Caltech. Now he has his own SURF students.

SURFIN' SAFARI

Thirty-one years ago, Caltech junior Ken Libbrecht was one of 17 students in the Institute's new Summer Undergraduate Research Fellowships program, or SURF, as it quickly came to be known. At the time a unique program, SURF offered undergraduates the opportunity to pursue original, hands-on research in close collaboration with faculty mentors. The students could choose the area in which to work—a junior committed to chemistry might spend 10 weeks studying earthquakes, or a sophomore undecided about whether she *really* wanted a post-college career in the laboratory might have a better idea about it after 10 weeks of communing with a collection of petri dishes.

Whatever the neophyte researchers elected to do, the whole idea was to give them a sense of how research actually works, from that first crucial step of submitting a proposal to the final formidable one of writing a research paper. Each SURFer received a summer stipend, came to know their faculty advisers as colleagues and friends, and went on to present their research at a SURF symposium modeled on professional conferences. By the time they left Caltech, several had also put their names to one or more published articles while they were still undergraduates. Above all, they had gained a firsthand appreciation of the research experience.

Libbrecht, a physics student, spent his SURF summer working with fellow physicist and Caltech professor Steve Koonin on an aspect of nuclear theory, which resulted in a paper in the highly regarded *Physical Review Letters*. Now himself a Caltech physics professor for more than a quarter century, Libbrecht is still involved with SURF. But these days, *he's* the mentor.

Although the basic elements of SURF remain the same, quite a bit has changed since 1979, when 17 students worked with 16 mentors. This year 431 students are working with 261 mentors. The SURFers include 53 undergrads from other schools who have come to Caltech to do research; 46 who are working with scientists at Pasadena's world-renowned Jet Propulsion Laboratory; and a number of Techers who are SURFing offsite at other university campuses, national laboratories, or high-tech R&D companies.

After all this time, SURF boasts many alumni, including current Caltech professors. Two of them, John Dabiri and John Johnson, were both undergraduates at other universities when they took part in SURF, and both say the experience had a significant impact on their careers.

Back in 2000 Dabiri was an undergrad at Princeton, "and Caltech wasn't on my radar at all," he says. "I told one of my professors that I was interested in doing summer research in experimental fluid mechanics, and he suggested the names of a few professors around the U.S., including Mory Gharib, a Caltech professor in aeronautics. I had never been to California (or on a plane!), so this seemed like a good excuse."

Dabiri enjoyed that SURF summer so much that he came back to Caltech for a PhD, with Gharib as his thesis advisor. Now an associate professor of aeronautics and bioengineering, Dabiri says, "My SURF involved measurements of jellyfish swimming. I wasn't thrilled when I first heard about the project because I didn't think biology could be rigorous. But I fell in love with biological fluid mechanics, and I have been doing it ever since."

Thinking he might want to attend Caltech as a graduate student, Johnson, then an undergrad at the University of Missouri-Rolla, saw SURF as "an opportunity to learn more about life at Caltech, build up research experience, and hopefully get a letter of recommendation from a Caltech prof."

Johnson, who did his SURF with Caltech's Laser Interferometry Gravitational-Wave Observatory (LIGO) research team, has since moved on to observational astronomy, identifying and studying planets beyond our solar system. He credits his SURF experience with helping him realize that he'd rather work in a smaller research group than in a large consortium. "It taught me that I love research, but that I needed a research question of my own."

Dabiri adds, "I think SURF can be eye-opening for students who are used to classroom learning, where someone else has already solved all of the questions. In research they get to experience the frustration and exhilaration of learning something no one else knows. That certainly was my experience."

When Libbrecht returned to Caltech after receiving his PhD at Princeton, he had no doubt that he wanted to mentor SURF students himself, a sentiment echoed by Dabiri and Johnson. Still, Libbrecht acknowledges that the experience can be a bit bittersweet. Johnson was his SURF student back in '99, and, says Libbrecht, "A person feels old when your SURF students have their own SURF students!"

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This article originally appeared online in Caltech Today the week of July 13. A few days later, we received an email from Jim Morgan, Goldberger Professor of Environmental Engineering Science, Emeritus. He was curious as to whether his former student Jim Jensen had been one of those original 17 SURFers in 1979. Indeed he had. The two men have kept in touch over the years, and it turns out that both remember that first SURF summer.

"Great guy all around," says Jim Morgan of Jim Jensen. "I still remember Jim playing in the pep band. . . ." As to the importance of SURF, Morgan opines, "I believe that SURF was instrumental in stimulating his interest in a future career."

Jensen agrees, saying, "Before my SURF experience, I had no idea what research entailed. I was hooked instantly by the open-ended nature of research, by the collaboration with Jim and his graduate students, and by the small victories and seemingly enormous challenges."

Jensen now says that one of his biggest pleasures—as academic director of the University at Buffalo's Research Exploration Academy and professor in the department of civil, structural, and environmental engineering—is having "the privilege of introducing undergraduates to the joy of research."

"As I work with underclassmen in our research seminars, I often think back to those sunny summer days in Keck Lab and ask, 'What would Jim Morgan do to inspire them?'"

Jensen's 1979 SURF project looked at how metals behaved in the presence of analogs of naturally occurring organic matter. After graduating from Caltech in 1980, he went on to receive his PhD at the University of North Carolina at Chapel Hill, continuing to work on naturally occurring organics. First as a graduate student and then as a young professor, he was elated to meet some of the people who wrote the papers that had inspired his SURF project. "SURF taught me about the community of scholars I was about to join."

After that memorable summer of '79 "elbow-deep in glassware and chemicals," Jensen enjoyed another first—becoming one of the first three SURF students to make a presentation to Caltech's Board of Trustees. "The trustees were gracious and pretended not to notice my shaking knees," he says. In hindsight, he says, that SURF summer, complete with Board presentation, gave him the confidence and enthusiasm to think seriously about pursuing his own research and teaching career.

It's been a career marked by a long line of Jensen's own graduate students, numerous awards and scientific papers, and two books. And now he's working on his third: the fourth edition of *Aquatic Chemistry* by Werner Stumm and—yes—James J. Morgan. The book remains the definitive resource on the essential concepts of natural water chemistry—in fact, it's considered by many to be the field's bible.

"I was deeply humbled when Jim approached me about revising the book that he cowrote. I never dreamed that I'd be writing the fourth edition of a book that we used in his class all those years ago," says Jensen.

Adds Morgan, "And only thirty years gone by." —*PD* E&S

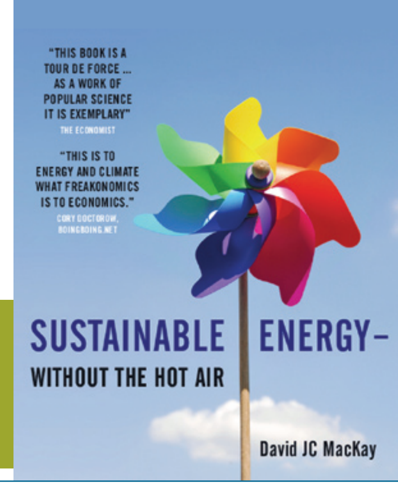
Former SURFer Jim Jensen is now on the faculty at the University at Buffalo.

Sustainable Energy—Without the Hot Air

The statistics thrown around in the sustainable-energy debate are often chosen to impress rather than inform. “Los Angeles residents drive 142 million miles—the distance from Earth to Mars—every single day.” Sometimes there are no numbers at all, just adjectives: “We have a *huge* amount of wind energy just waiting to be tapped.” But how does that “huge” compare to the hugeness of our energy consumption?

David MacKay (PhD ’92), the Chief Scientific Advisor to the United Kingdom’s Department of Energy and Climate Change, has done the math. He offers a simple, common-sense analysis that answers such questions as, “Can the U.S. live on its own renewable energy sources?” and “If everyone turns off their cellphone chargers when not in use, will an energy crisis be averted?”

MacKay at the Houses of Parliament with the most efficient form of personal transportation ever developed. It uses just one kilowatt-hour (derived from biofuels!) per 100 person-kilometers—80 times better than a car.



By David MacKay

I'll take it as given that we're motivated by at least one of three compelling reasons to stop using fossil fuels. First, easily accessible fossil fuels are a finite resource; at some point, that resource will run out. Second, setting fire to fossil fuels puts out carbon dioxide—a vast geoengineering experiment with a very uncertain outcome. Third, even if you don't believe in climate change and even if *global* fossil fuels aren't going to run out today, maybe *your* fossil fuels are running out; so if you don't want to depend on other people for your energy, you might want to get off fossil fuels.

A lot of people get emotional about our energy options, but emotions alone will not get us where we need to go. I think it's important to have some numbers in the conversation, if we're going to have a constructive debate about energy options.

To make our supply and demand options comprehensible and comparable, I suggest measuring all forms of energy in one set of units, rather than switching between barrels of oil, terawatt-hours, and petajoules. To avoid having answers that involve incomprehensible millions or billions, I will estimate all energy and power figures *per person*. My rough guide to sustainable energy will measure energy in kilowatt-hours, and power—the rate of using or producing energy—in kilowatt-hours per day. By measuring powers in kilowatt-hours per day (rather than watts or kilowatts), it's clearer we're talking about a *rate* of energy consumption. I'll deliberately use rough, back-of-the-envelope numbers to streamline the calculations and permit fluent thought.

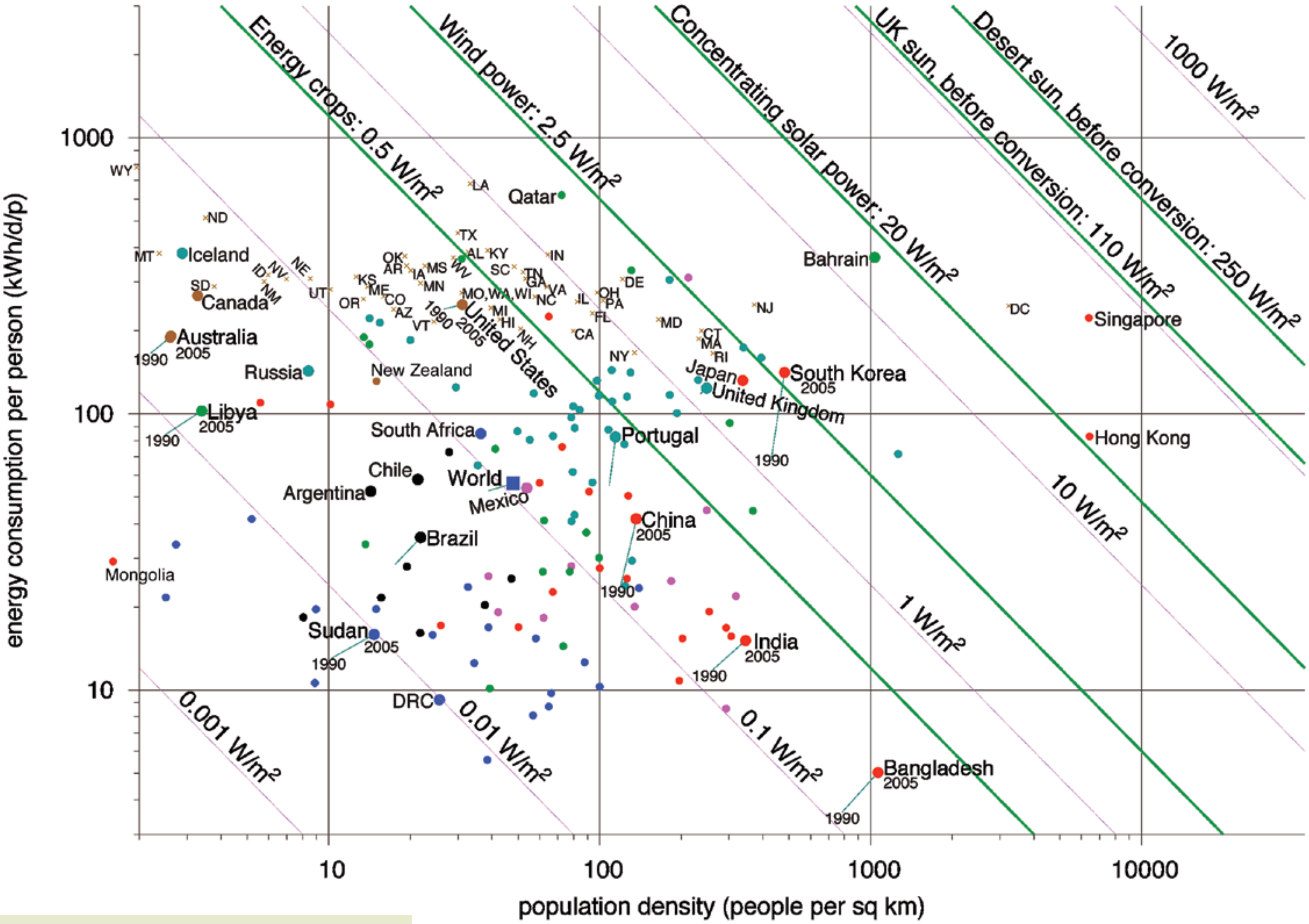
Everyday personal choices come in small numbers of kilowatt-hours. If you burn one 40-watt lightbulb for 24 hours, you use one kilowatt-hour of electricity, and it might cost you 10 cents. The chemical energy in the food you eat amounts to about three kilowatt-hours a day. If you take a hot bath, that's five kilowatt-hours of energy to heat the water. If you drive an average American car that gets 25 miles to the gallon on a trip of 100 kilometers, you use 80 kilowatt-hours of chemical energy. If you fly from London to Los Angeles and back, you use 10,000 kilowatt-hours—an incomprehensibly large number—but if you fly only once a year, your average power consumption comes out to 26 kilowatt-hours per day. And if you have a typical three-bedroom American house, you might be using 80 kilowatt-hours per day all told to run it. Share this between a family of three, and we're back down into the 25 kilowatt-hours per day ballpark.

These simple, easy-to-grasp numbers can be our lifeboat on the flood of crazy, innumerate codswallop that inundates us daily from all sides of the energy debate. For example, a 2007 ad campaign said that if every London household unplugged their cell-phone chargers when not in use, we could prevent 31 *thousand* tons of CO_2 from getting into the air a year. Sounds like these black, planet-destroying objects are about as evil as Darth Vader. But let's just check the numbers: a cell-phone charger left plugged in uses about half a watt, so the energy saved by switching it off for a whole day is 0.01 kilowatt-hours, which is exactly equal to the energy used by driving an average car for one second. I'm not saying don't switch it off, but perhaps when we're trying to make a plan that adds up, cell-phone chargers should be some way down on the list of priorities for public information campaigns.

The total energy consumption of the United States divided by the nation's population is 250 kilowatt-hours per day per person. (Britain and the other European countries use half that amount, 125 kilowatt-hours per day per person. Australia and Canada use about 300.) You can think of this as every American having 250 40-watt lightbulbs burning all the time. One kilowatt-hour per day is also the approximate power output of a human servant, so it's as if, in the modern age, we each have 250 mechanical servants on staff. This energy goes into transportation, into heating and air conditioning, into electricity, and into the making, distribution, and ultimate disposal of *stuff*—soda cans, sweat socks, patio furniture, the latest techno-gadget, and even this magazine. There are other uses of energy, too, but the big three forms of consumption that you need to focus on for a quick conversation about energy options are transportation, heating, and electricity.

RENEWABLE ENERGY SOURCES

Most forms of renewable energy involve doing something on an area of land; to understand how easy it would be to live mainly on renewables, we need to talk about their power production per unit area and compare it with our power consumption per unit area. If we plot the number of people per square kilometer against the energy consumption per person, as shown at the top of the next page, we can read off the power consumption per unit area for a given country, state, or region. The world's average power consumption is 0.1 watts per square meter. The United Kingdom consumes about 10 times that, 1.25 watts per square meter, and America is at about



Above: Plotting population density versus per-person energy consumption gives us power consumpion per unit area. (The turquoise dots are the European countries.)

At the top left are places with very low population density and very high per-capita consumption, like Iceland. Top right, Bahrain consumes as much energy per person as Iceland, but has more than 100 times the population density. Bottom right, Bangladesh has the same population density as Bahrain, but uses only five lightbulbs per person, nearly 100 times less. A lot of countries, especially in Africa, used to be down at the bottom left, but they're all rushing up and to the right, as is the world average. This is shown by the tails on some of the dots, which track population and consumption growth from 1990 to 2005.

Both axes are logarithmic, so we can draw diagonal lines (green) to show how much power per square meter various forms of land-intensive renewable energy can produce. If a dot lies below and to the left of a green line, that energy source could meet all of that country's needs, and the distance between that dot and the line gives one an idea of how much land would be left over to live on, plant crops on, and so forth.

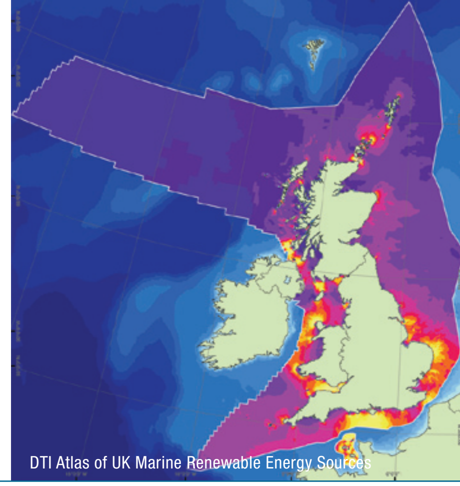
0.3 watts per square meter. Renewable energy sources also come in watts per square meter, so we can put them on the same plot and see how they compare.

Wind power, for example, offers an average of 2.5 watts per square meter for good, windy locations in Europe. That is twice the power consumption per unit area of the United Kingdom, so if you ask, "Can Britain power itself completely on wind?" the answer is, "Yes, if half the area of the U.K. is occupied by wind farms."

Energy crops deliver about half a watt per square meter in European climates, so if you covered the whole of the U.K. with energy crops, you wouldn't match today's power consumption. On the other hand, the U.S. could cover itself with energy crops and match its consumption with a little bit to spare. So there are different messages for different countries. In the tropics, by the way, temperatures are warmer and plants are more productive, so you might get perhaps 1.5 watts per square meter in Brazil.

All renewables are in the same ballpark. Rooftop solar panels in Britain deliver about 20 watts per square meter; in sunnier countries perhaps you could get double that. But rooftops are relatively small, so even if you covered every south-facing roof in Britain with solar panels, they would only deliver about five lightbulbs of power per person. If you want to get up to the scale of our actual consumption, you have to go a bit crazy and coat the countryside with solar panels, too. But there will be gaps between the solar panels, so the net power output is about five watts per square meter—twice as good as a wind farm, but still, if we wanted to match Britain's power consumption this way, we'd need solar farms roughly one quarter the size of the country. Tidal pools come out about the same as wind power, offering roughly three watts per square meter. So, again, to match today's consumption, you'd need a tidal pool the size of a country—and God in His wisdom, when He created the British Isles, provided precisely such a facility. It's called the North Sea. The North Sea is a natural tidal pool, in and out of which, and around which, great sloshes of water pour every 12 hours. If we put huge underwater windmills where the currents are big we could get something like eight watts per

Courtesy of SunPower Corporation



DTI Atlas of UK Marine Renewable Energy Sources

Far left: A traditional Bavarian farming method as practiced near Mühlhausen, Germany.
Left: The tidal-driven current flows in the areas shown in yellow on this map are capable of producing eight watts per square meter.

square meter of underwater windfarm, which could make a significant contribution to powering the U.K. However, this is a rather uncertain figure because we don't have any underwater wind farms yet, just a couple of prototypes.

If you deploy arrays of lenses or mirrors in the desert, and use them to concentrate sunlight onto collectors, you can get up to 15 or 20 watts per square meter of land area, according to the manufacturers of such arrays. Below right is an individual concentrator that will, on average, deliver 140 kilowatt-hours per day—a bit more than what's needed to power the lifestyle of the German woman standing beside it.

The key lesson is that all renewables are diffuse, and if you want them to make a significant contribution compared to today's consumption, the renewable-energy facilities have to be country-sized. And this presents problems, because while some people love the idea of harvesting renewable energy by dotting the landscape with windmills or solar panels, many don't want such things in their backyards.

So how can we make an energy plan that adds up? Perhaps we could reduce demand. Do we really *need* 125 or 250 lightbulbs' worth of power per person? One way to reduce demand would be to change our lifestyles. I used to give energy talks that recommended lifestyle change, but they did not always go down well with audiences, so my strategy now is to just be the numbers guy: I don't make any recommendations, except that, whatever choices we make, the numbers must add up. So let's take the question of lifestyle change and leave it to one side; we can come back to it again later on, if we want. There's a second way to reduce demand: technology! We are at Caltech, after all. Let's use technology that's more efficient, reduce demand by being smart, and then figure out what needs doing on the supply side.

Wind power offers an average of 2.5 watts per square meter, so if you ask, "Can Britain power itself completely on wind?" the answer is "Yes, if half the area of the U.K. is occupied by wind farms."

THE DEMAND SIDE

I'll start with transportation. Standard petrol and diesel engines are only about 25 percent efficient at turning chemical energy into oomph. In contrast, electric vehicles convert chemical energy in the battery into oomph at the wheels with an efficiency of 85 or 90 percent. Electric vehicles use only about 20 kilowatt-hours per 100 kilometers. That's about four times better than a standard fossil-fuel vehicle, which uses 80 kilowatt-hours per 100 kilometers. Of course, if you get your electricity by burning chemicals at a power station with an efficiency of only 30 percent or so, this isn't helping very much. But there are other ways to make electricity; if we transform our electricity-generating system, electric vehicles may help us make a plan that adds up.

Left: PS10, a solar concentrator plant near Seville, Spain, uses a field of mirrors to focus sunlight on a tower to heat water that spins a turbine to generate electricity. This facility generates about 5 watts per square meter of land area, on average.
Right: The 5,760 lenses in Amonix's solar array focus sunlight onto individual photovoltaic cells. At 140 kilowatt-hours per day, it could match the average energy consumption of one European or half an American.

Right: In Japan, caped crusaders Tankman and Pumpu are here to save the day. And yes, the name of the system really *is* Eco-Cute. "Kyuto" in Japanese means "to provide hot water." Far right: The actual hardware provides domestic hot water as well as heating the house.

As a transition to electric vehicles we could drive plug-in hybrid cars, which are electric vehicles that you can recharge overnight from a wall outlet. Plug-in hybrids mainly work like electric vehicles, but they have a small emergency fossil-fuel engine on board to extend the vehicle's range. When running on electricity, the Chevy Volt is expected to use 25 kilowatt-hours per 100 kilometers, which is still a big win, as long as we have somewhere satisfactory to get the electricity from.

Now let's talk about heating. In winter, you can reduce the heat loss from your house with an amazing technology called a thermostat. You grasp it, you rotate it to the left, and it will, if you turn it down one degree centigrade, reduce the heat loss by 10 percent in a typical British house. Turn it down five degrees, and you'll get a 50 percent saving in the power required to heat the house. Tinkering with thermostats is crucial. The standard thermostat keeps a building obsessively at one temperature, but humans don't want a particular temperature. If you have just cycled home on a freezing cold night and you come into a building that's only 13 centigrade rather than the 20 centigrade that many people now think is essential, it feels really warm—at least for an hour or two, and, if you're only going to be in the building that long, there's no need to heat it. Just putting the thermostat on a clock isn't enough. We need to know if there is anyone in there, and do they feel cold?

Another option is more efficient heat creation. One standard way of making heat is to set fire to natural gas, at an efficiency of about 90 percent. This sounds pretty good, but it's actually really lousy, because you're taking high-grade chemical energy and turning it into low-grade heat.

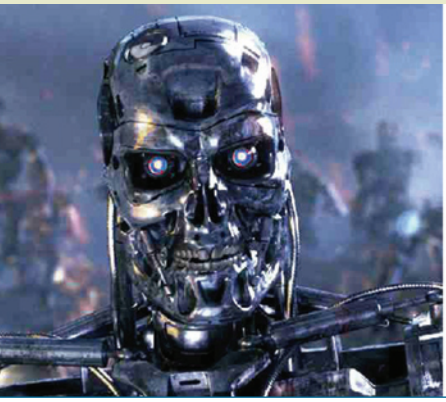
We can deliver low-grade heat with far greater efficiency with a heat pump, which is a back-to-front refrigerator. Your fridge is cold inside because it moves heat from where the food is out to the grill on the back. Take the door off the fridge, put the open fridge in the kitchen window, and it will cool down the garden. But it's still warming the kitchen, where the grill is.

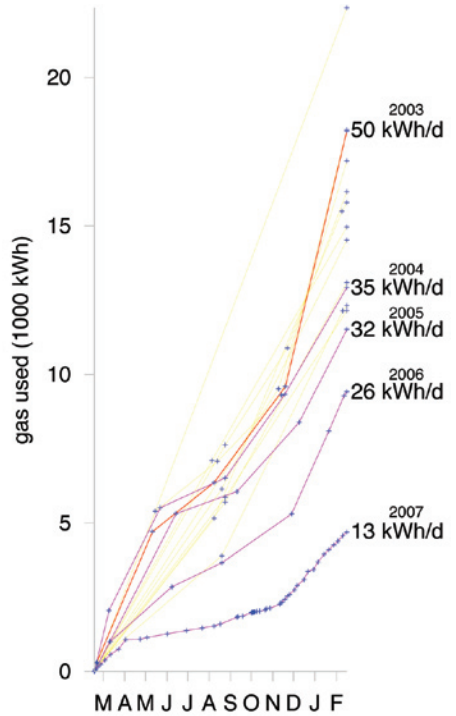
In Japan they've recognized the importance of heat pumps for decades, and the results are wonderful. According to the manufacturers, you give Pumpu (above) one kilowatt-hour of electricity, and he'll deliver 4.9 kilowatt-hours of heat by moving it from the garden into the kitchen and into Tankman. Not 90 percent efficiency, but 490 percent efficiency! So trading in all our natural-gas furnaces for electrically powered heat pumps would make a huge difference.

But the single most significant energy-saving technology is called "Read Your Meters!" Here's how it worked for me. When I started writing my book on energy, a friend asked me, "So, how much energy do you actually use?" I was embarrassed that I didn't know the answer, so I started reading my gas and electricity meters every week, and the answer completely changed. I used to use 40 or 50 kilowatt-hours per day of natural gas, and I got that down to 13 kilowatt-hours per day. Similarly, my electricity consumption went down from four kilowatt-hours per day to two kilowatt-hours per day. It's a video game, really—you want to beat last week's score, and so you try experiments.

I switched off not only the phone charger (haha), but also the DVD player, the stereo, the cable modem, all those devices that draw juice even when they're just sitting idle.

Plug-in hybrids, like the soon-to-be-released Chevy Volt, may provide a useful transitional technology on the way to all-electric vehicles. I'm not sure why they have to look like killer robots from the future.





In general, you can reduce the heat loss from your house with an amazing technology called a thermostat. You grasp it, you rotate it to the left, and it will, if you turn it down one degree centigrade, reduce the heat loss by 10 percent in a typical British house. Tinkering with thermostats is crucial.

I saved one kilowatt-hour per day, which is worth having. It's one percent of the average European's footprint. It also saved me 45 pounds a year—which I can spend on an extra holiday in the Canary Islands! This brings me to Jevons's paradox, which says that when you develop a new, more energy-efficient technology, you may well end up using more energy overall. I don't know an easy way around Jevons's paradox, but we'll have to bear it in mind as we pursue technological fixes.

THE SUPPLY SIDE

Even with these efficient technologies reducing demand, we'll have to broaden our supply options in order to make a plan that adds up. For many countries, renewables alone simply won't be enough.

One supply option is called "clean coal with carbon capture and storage," which means let's carry on using fossil fuels, but do something smarter with the carbon dioxide. The plan would be to pump CO_2 into the ground, where we intend it to stay for thousands of years; this technology has yet to be demonstrated at scale.

We could use nuclear power, which has popularity problems. Nuclear waste is nasty stuff. I don't want it in my pocket, but the wonderful thing about it is that it *would* actually *fit* in my pocket. The volume of British nuclear waste generated per person each year would almost fit in a wine bottle. The low-level waste is 760 milliliters, the intermediate-level waste is another 60 milliliters, and the 25 milliliters of high-level waste would be the sediment at the bottom of the bottle. So it's a nasty problem, but I think it's solvable.

We could very politely ask other countries, "Please, can we have some of your renewables? We don't want to build them in our back yard." This could also work on smaller political scales: you can imagine Massachusetts, which has the same population density as Britain, asking to borrow some of Arizona's desert.

Incidentally, there used to be an international trade in negative energy—about 100 years ago, Norway used to export *cold* to London in the form of ice.

There's one other thing: whatever plan we propose, demand and supply must add up *at all times*—during all weeks and all minutes throughout the year. Demand fluctuates. Electricity demand fluctuates on a daily cycle. Natural-gas demand for heating peaks in the winter and drops in the summer; in fact, in Britain it can more than double in midwinter. So we need a plan for storing energy in order to level out demand on all time scales.

You can level out hourly electrical demand by "pumped storage," which uses water in a mountaintop reservoir as a battery. You pump the water up to the reservoir, turning electrical energy into potential energy, and then later you let the water run back downhill through the turbines to generate electricity.

On a seasonal scale, you can pump solar-heated water into the ground in summer, and pump it back out in winter. There's a master-planned community called Drake Landing up in Alberta that has been doing this since 2007. They claim to have halved the usual natural-gas consumption for heating, which leads me to wonder why they didn't build everything to better insulation standards so that they wouldn't need any gas heat in the first place.

When I started reading my gas meter every week, my consumption plunged. To help me tinker with the thermostat, in 2004 I got a more sophisticated time-controlled model, and installed a thermostatic valve on every radiator in the house. I also replaced my boiler with a condensing boiler that extracts latent heat from the steam produced by setting fire to methane. I scored again in 2007 by having fluff insulation blown into the outside walls and attic and buying new double-glazed windows and doors.

JEVONS'S PARADOX

Coal was to Victorian technology as oil is to ours. As steam-powered machinery proliferated, coal consumption skyrocketed, and the question of how long Britian's reserves would last was hotly debated. In 1865, economist William Stanley Jevons published *The Coal Question*, in which he calculated that demand was doubling every 20 years—a clearly unsustainable rate—and predicted that "Rather more than a century of our present progress would exhaust our mines to the depth of 4,000 feet, or 1,500 feet deeper than our present deepest mine." (In fact, British coal production peaked in 1910.)

In the book, Jevons described the paradox now named for him: "It is wholly a confusion of ideas to suppose that the economical [i.e., efficient] use of fuel is equivalent to a diminished consumption. The very contrary is the truth. . . . It is the very economy of its use which leads to its extensive consumption . . . if the quantity of coal used in a blast-furnace, for instance, be diminished in comparison with the yield . . . the price of pig-iron will fall, but the demand for it [will] increase; and eventually the greater number of furnaces will more than make up for the diminished consumption of each."

At an average of 15 watts per square meter, harvesting concentrated solar power in the desert is our best option among the renewables. The yellow squares on this map are 600 kilometers on a side. Completely filling one of them with solar concentrators would supply power for a billion people at the European standard of consumption; doing the same for the world would require *two* such squares 1,000 kilometers on a side.

A PLAN THAT ADDS UP

So how do you we take a place like the U.K.—or Massachusetts, or New Jersey, or anywhere with a high population density—off fossil fuels? It would involve electrification of lots of transportation; flying less; riding your bike and taking the train more; insulating buildings better; getting people to read their meters; and electrifying building heating using heat pumps. And then you would meet the vastly increased demand for electricity from a mix of your own renewables; possibly nuclear power, which is a stopgap in the sense that uranium and thorium atoms are a finite resource on the scale of a millennium; possibly clean coal, which is also a stopgap, because coal is a finite resource on the scale of decades or centuries; and, finally, other people's renewables, which could be solar power in other people's deserts.

The wind farms needed to deliver 42 kilowatt-hours per day to the U.S. would cover 10 New Jerseys. Biofuels would take about 50 New Jerseys.

I'm emphatically *not* recommending any particular solution. My goal is to show you, to scale, all the options that are on the table, and the exchange rates among the different sources, so that there can be an informed discussion. If someone says, "I don't want solar power from someone else's desert, thank you," no problem—for each 60 square kilometers of solar power you cut, you need another one-gigawatt nuclear power station. Or if you say, "No no no, I don't like nuclear power," no problem—each nuclear power station can be replaced (on average) by 2,000 wind turbines, occupying an area of about 400 square kilometers. Then you just need to decide where you're going to put all those extra wind farms.

People often say, oh, a tiny square in the Sahara could satisfy all the world's energy consumption. Each yellow square in the map above would enable a European standard of living for everyone in Europe and North Africa—125 kilowatt-hours per day per person for one billion people. (The red square is for the population of Britain, or 60 million people. Fittingly, it's the size of Wales.) The yellow square is much smaller than the Sahara Desert, yes, but it is the size of Germany. So the message is, and always will be, that we're talking about a big building project. And if you want to mix in other renewables, fine, but the total area will only get bigger, because other renewables have *lower* power per unit area. If we put that same yellow square in North America, it would deliver your consumption—250 kilowatt-hours per day per person—for everyone in Canada, Mexico, and the U.S., and it would be half the size of Texas.

You don't want to just depend on arrays of solar panels, so let's sketch out some options. If the U.S. is serious about getting off fossil fuels by 2050, you could go for wind, nuclear, biomass, and solar-in-the-deserts in a big way.

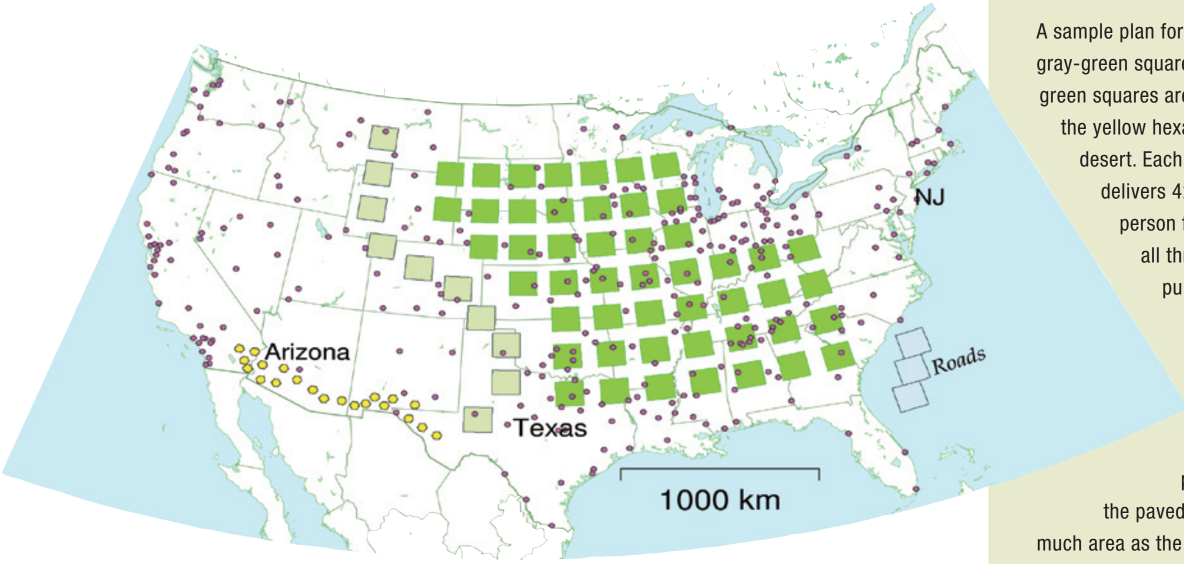
To show you the exchange rates, I'm going to map out 42 kilowatt-hours per day per person each of wind, of nuclear, of biomass, and of solar in deserts. That adds up to 168 lightbulbs per person, which, if some energy-saving measures are introduced, might maintain today's lifestyle. (Putting solar hot-water panels on your roofs would supply about half your residential hot-water needs in almost all climates, for example.)

As you can see from the map on the opposite page, the wind farms needed to deliver 42 kilowatt-hours per day per person would cover 10 New Jerseys, or about the area of California. The arrays in the desert to concentrate sunlight stations would be one-eighth of the size of Arizona. Energy crops are shown by the green squares in the Midwest—about 50 New Jerseys. And the nuclear plants, each about a kilometer square, would be a fivefold increase over today's levels.

Let me now personalize this. What does a community need to do? What does one person need to do? If 300 people say, "Let's get ourselves a wind turbine," and it's a standard two-megawatt turbine, that's 42 kilowatt-hours per day per person on average.

Los Angeles would be getting 42 kilowatt-hours per day per person from nuclear power if the city had—for itself—seven one-gigawatt power stations. Chicago would need five; Houston, four; Denver, Boston, Las Vegas, and Portland, Oregon, one each. Your biomass plantations, at 4,000 square meters per person, would be half of a football field devoted *to you* to deliver your 42 kilowatt-hours. And the solar-in-deserts would need 30 one-meter-square mirrors per person, focusing sunlight on a 1/400th share of a centralized collector tower.

What about the cost of building all these things? Money's important, but I give a physics-based talk because the laws of physics are timeless, whereas the "laws" of economics can change within 12 months. Nevertheless we can estimate the costs. At today's prices, British offshore wind farms cost twice as much, in terms of subsidies, as British onshore wind farms. Nuclear and clean coal's costs are unknown, because no one's built a nuclear power station in the last



A sample plan for the United States. The gray-green squares are wind farms, the bright green squares are bio-energy plantations, and the yellow hexagons are solar plants in the desert. Each of these three renewables delivers 42 kilowatt-hours per day per person for 300 million people, and all three are drawn to scale. The purple dots are your industry-standard one-gigawatt nuclear power plants (not drawn to scale) providing another 42 kilowatt-hours per day per person. For comparison, all the paved roads in the U.S. take up as much area as the three squares in the Atlantic. Each square is 20,000 square kilometers in size—the same area as New Jersey.

couple of decades, and clean coal is still at the pilot-plant stage. Hopefully they'll come in similar to onshore wind farms, but the error bars on costs are really quite large at the moment.

The total cost of doing something like this for Britain would come out to something like 14 billion pounds per year. Britain already spends 100 billion per year on energy, and another 100 billion on insurance. So 14 billion a year over the next 40 or so years compared with 200 billion a year sounds quite reasonable to me—you could view this as an energy and insurance policy all wrapped up in one. It's still a substantial number, and figuring out how to finance these things is going to be a challenge. But it's not unaffordable. It seems to me to be a solvable problem.

It's not going to be easy to make an energy plan that adds up; but it is possible. We need to make some choices and get building. E&S

David MacKay (PhD '92) took his BA in natural sciences at Trinity College at the University of Cambridge, and came to Caltech on a Fulbright, founding the Caltech Environmental Task Force while earning his degree in computation and neural systems. He then returned to Cambridge, where he is now a professor of natural philosophy at the Cavendish Laboratory. He was elected a fellow of the Royal Society in 2009. As a physicist, his reseach focuses on information theory and machine learning.

As an environmentalist, MacKay says he was inspired by "reading **Caltech News** ***in the bath one evening when I came across an article by [Caltech physics professor David] Goodstein" warning that we could run out of cheap oil within the decade. But MacKay was also reading*** **The Skeptical Environmentalist,** ***by economics professor Bjorn Lomborg, who said that "everything is fine, there is plenty of energy. How could two intelligent people reach such different conclusions?" At the same time, MacKay was getting fed up with the "twaddle" in the form of incomprehensible, misleading, or downright wrong numbers being put out by the media, politicians, corporations trying to appear green, and environmentalists alike. This turned into a bunch of back-of-the-envelope calculations he posted on a website, which eventually turned into*** **Sustainable Energy — without the hot air,** ***an eminently readable, vastly entertaining, and remarkably thorough analysis of our energy options.***

The book brought him a job offer from the U.K.'s Department of Energy and Climate Change, where he is now responsible for ensuring that scientific and engineering evidence underpin all the Department's work—the U.K. equivalent of former Caltech physics professor Steven Koonin (BS '72), who is now the Under Secretary for Science at the U.S. Department of Energy.

One of the U.K. Department's new projects is an engineering-based software tool to explore how demand-side and supply-side choices can be combined into energy pathways that maintain security of supply, and achieve Britain's target for greenhouse emissions reductions of at least 80 percent below 1990 levels.

This article was adapted by Douglas L. Smith from the presentation MacKay gave at Caltech on April 5, 2010. A video of the talk can be seen in the Caltech Streaming Theater. Go to http://today.caltech.edu/theater/list?subset=science.

Sustainable Energy — without the hot air ***can be ordered from the Caltech bookstore at: www.caltechstore.caltech.edu. The book is also downloadable (for free!) in whole or in parts at www.withouthotair.com.***

Discovering New Worlds

As a kid, John Johnson wasn't interested in astronomy—or even science for that matter. But now, as an associate professor of astronomy, he's discovering entirely new worlds. In this interview, he talks about the search for planets and the rapidly evolving field of exoplanet astronomy.

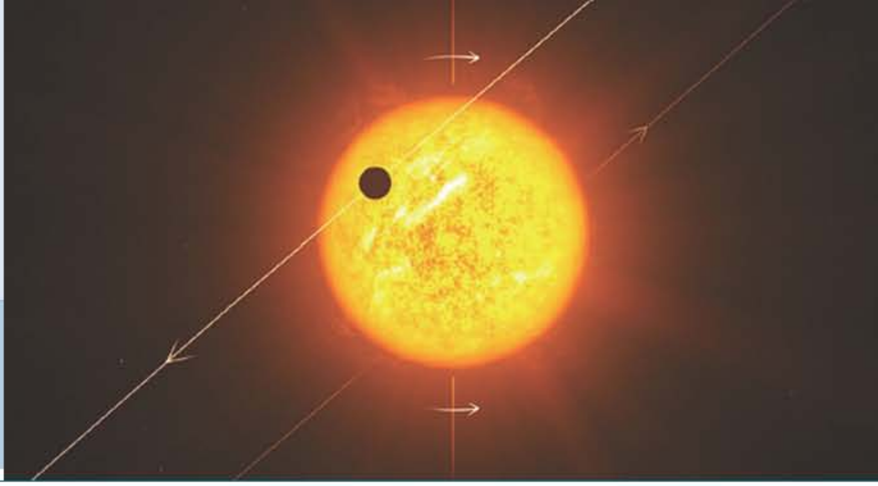
In high school, John Johnson wanted to be a fighter pilot. But when he learned that sinus problems would prevent him from flying planes, he declined his admission to the Air Force Academy and enrolled at the Missouri University of Science and Technology to study engineering. "I figured I'd build planes if I couldn't fly them," he says. There, he discovered a passion for science, and graduated with a degree in physics in 1999. That summer, he did a Summer Undergraduate Research Fellowship (SURF) at Caltech, working on the Laser Interferometer Gravitational-Wave Observatory (LIGO) project. He was admitted to UC Berkeley's graduate school in astronomy, and when he visited the campus, he learned about exoplanets—planets that orbit other stars—and fell in love. In fact, he had only just read about them in Astronomy magazine the day before his visit, in an article of which Berkeley astronomer Geoff Marcy was a coauthor. Marcy, as he would soon find out, is a pioneer in the study of exoplanets, and has discovered more planets than anyone in the world. "Over those two days, I learned what exoplanets were," Johnson says. "I guess I had heard about them, but it dawned on me that there were 33 of them—and that was amazing." And when he realized that the field was so young that even third-year graduate students were writing significant papers, he was sold. "This is what I want to do," he says. "I want to make big discoveries. I want to find something new."

Working with Marcy, he became an expert planet hunter, earning his MA and PhD in 2002 and 2007, respectively. After a stop at the Institute for Astronomy at the University of Hawaii as a National Science Foundation Astronomy and Astrophysics Postdoctoral Fellow, he came to Caltech as an assistant professor of astronomy in September 2009. In the following interview, he discusses the search for planets and the rapidly evolving field of exoplanet astronomy. Today, mainly by measuring the slight wobble of stars caused by the gravitational tugs of their planets, astronomers have discovered more than 430 exoplanets—and the number is rising every week.

What's the focus of your research?

Broadly speaking, we want to find new planets around other stars, which are commonly referred to as exoplanets. We're building up a huge statistical sample. When you have a large number of planets, you can start looking for patterns, trends, and hints

Left: John Johnson in front of the 200-inch Hale Telescope at Caltech's Palomar Observatory.
Right: This artist's conception shows a planet in a highly tilted orbit around its star.



By Marcus Y. Woo

about the planet-formation process. The primary goal of my search for planets is to understand planet formation and therefore to understand the origins of the solar system. My characterization work is focused on individual systems of planets or the planets themselves. We're trying to learn about their physical characteristics, such as their radii, masses, average densities, and atmospheric properties. For systems of planets, we're interested in how planets interact gravitationally with one another. The exact nature of those gravitational interactions gives us hints about how planetary orbits evolve after they form. And that probably has a lot to do with how architectures of planetary systems eventually come to be.

What are some of the current big questions that you guys are trying to tackle?

We're interested in how the solar system formed. We're interested in our immediate environment and describing its origins. And beyond that, we're interested in general in how planetary systems formed. There are some very specific questions that arise at every turn. There are so many surprises in this field—almost nothing is turning out as we expected. There are Jupiter-mass planets in three-day orbits. There are planets with masses that are between those of the terrestrial planets in our solar system and the gas giants in the outer part of our solar system. There are Jupiter-mass planets with hugely inflated radii—at densities far lower than what we thought were possible for a gas-giant planet. There are giant planets with gigantic solid cores that defy models of planet formation, which say there shouldn't be enough solids available in a protoplanetary disk to form a planet that dense. There are planets with tilted orbits. There are planets that orbit the poles of their stars, in so-called circumpolar orbits. There are planets that orbit retrograde—that is, they orbit in the opposite direction of their star's rotation. There are systems of planets that are in configurations that are hard to describe given our understanding of planet formation. For instance, some planets are much too close to one another.

But a lot of those surprises have to do with the fact that we have only one example of a planetary system—our solar system—to base everything on, right?

What's interesting is that we've found very little that resembles our example.

What sort of planets are we finding often?

There are classes of planets that are unexpected—the so-called hot Jupiters, for example. That's a class of planet that's received a great deal of attention; I call them the bonus planets. To detect Jupiter-mass planets, you would've expected to have to wait about 12 years to see a complete orbit. But suddenly there were these Jupiter-mass planets with orbits of only a few days, making them easy to detect. You can fully characterize one of these planets with a week's worth of observations. Those planets weren't supposed to be accessible to us, but suddenly they are. So people are doing things like measuring their spectra, measuring their temperatures directly, and getting a handle on their atmospheric properties.

How do we think hot Jupiters form?

It's generally thought that they formed much farther out from their star, probably at a distance similar to where Jupiter is in our solar system. Then, they somehow migrated inward. They can migrate through a number of different mechanisms. One of the areas of my research is to understand what mechanism or mechanisms are largely responsible for the population of hot Jupiters.

Do astronomers have a favored mechanism?

Up until two years ago, the favored one was that the planet hitches a ride with the disk material. As the planetary system is forming, the disk material around a star starts to spiral inward. You can think of it as a bathtub draining, and the planet gets dragged along for that ride, and somehow gets stranded right next to the star. That theory was favored until about 2008 because most of the planets we found were well aligned. The star was spinning one way and the planet basically tracked the star's equator. It went parallel to the equator in the same direction as the star. That's what you would expect. The star got its angular momentum from the disk, the planet was formed in the disk, so they should still share that angular momentum vector today. But then we started finding tilted planets, and polar planets, and retrograde planets, and that theory has now gone into the dustbin. We're scrambling to find a new way of de-

There are so many surprises in this field—almost nothing is turning out as we expected.

To learn more and to watch a video demonstrating how astronomers detect exoplanets, go to John Johnson's website.

scribing how these gas giants can move in that also causes their orbits to be tilted.

Could it be that planets actually do spiral inward, but some other object comes into the picture and interacts with the system and tilts the orbit?

Personally, I'm not ready to give up on the old theory. I'm just reflecting what most exoplanet scientists think these days. I think we're getting fooled by a combination of selection biases. I have a grad student, Tim Morton, working on that right now, trying to understand what conclusions we can draw from the current sample; it's not as easy as you might think. It's analogous to trying to measure the average height of human beings by standing in the middle of a basketball court. Where you are and how you make that measurement really matters. You want to broadly sample a population—you don't want a myopic view of that population. If you stood in the middle of a Lakers game, you might report that the average height of a human being is six foot eight. We know that's not true. We have to be out in the stands.

How much has the field changed since you entered it as a graduate student 10 years ago?

I'm a specialist in measuring precise radial velocities or measuring Doppler shifts of stars as they move in response to their planet's gravitational tug. We've increased our precision in measuring those shifts by a factor of three, so we're able to see much smaller planets than we could back then. Overall, we've moved away from the era of stamp collecting, when it was really cool to find a planet, and a discovery immediately warranted a paper. Now we've moved to a regime where we have tons of detections and it's hard to get around to publishing them all because each exoplanet has relatively little impact. It just adds to the statistical sample. Nowadays, people have to stretch to find the defining characteristic of a given planet that they're announcing.

I couldn't go back to sleep. I was bone-tired, but I was excited and hyped up, so I got up and started working on the paper.

My own research has shifted to studying the statistics of large numbers of planets rather than any one planet.

You're studying the whole population rather than specific systems.

Yeah, I think that's where one of the frontiers is. That's where I'm trying to put my own research. For instance, we just published a new result based on the statistics of planets showing that the more massive a star is, the more likely it is to have a Jupiter-mass planet. That's telling us something very important about planet formation. A more massive star should have a more massive disk, and the more massive disk should have more raw materials for planet building. There's a competing theory of planet formation that says it shouldn't really matter how much mass you have in the disk. There should be other factors that govern whether that disk is going to turn into planets. So we were actually able to pit those two theories against one another, conduct this experiment, and test those predictions. I feel like we were able to make a pretty clear conclusion that it really does matter how much raw material you have in a disk for planet building.

Was that unexpected?

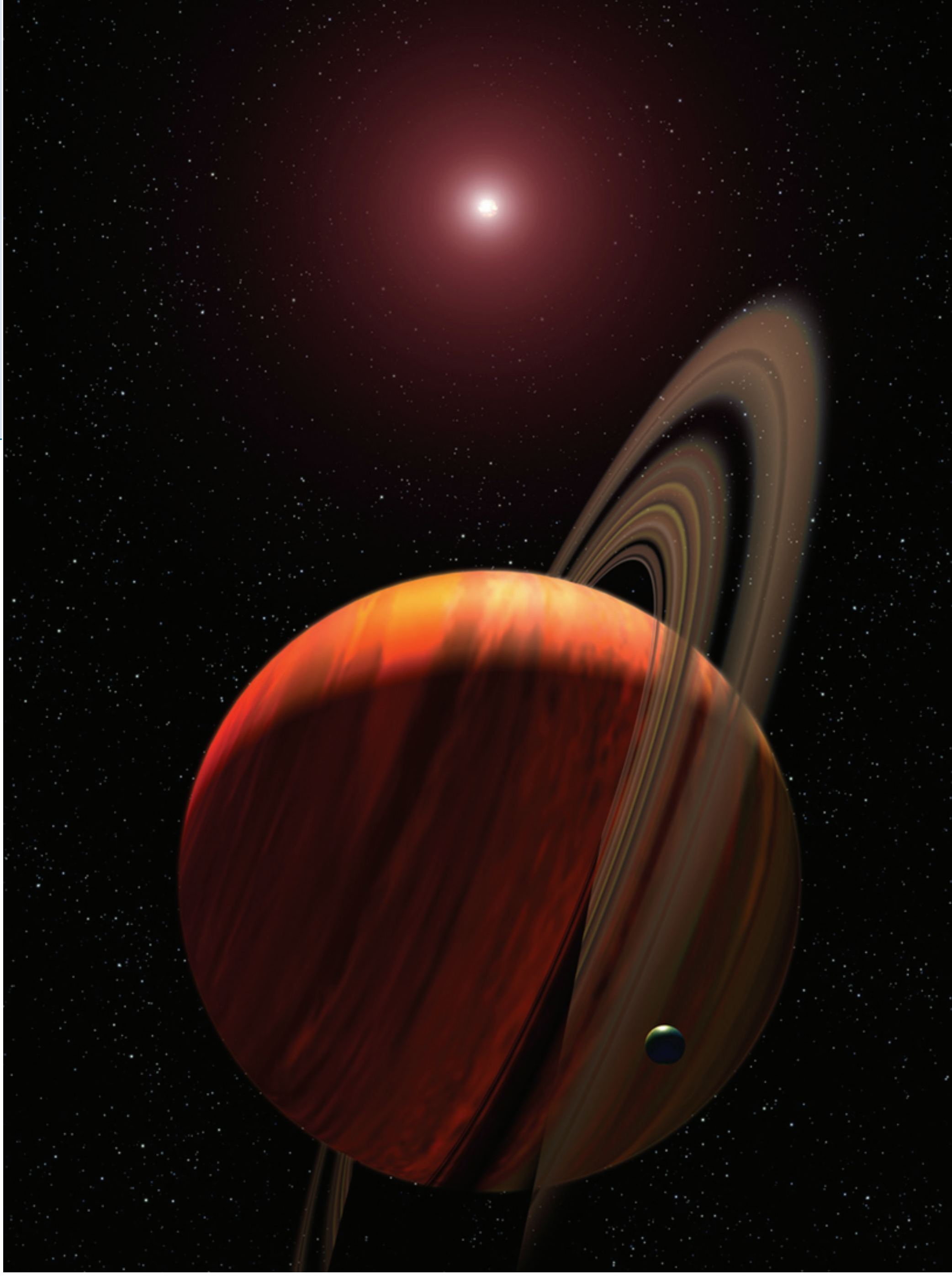
That was the theory of planet formation before we knew of exoplanets. Then when we found exoplanets, it was thought we might need a better theory. This old-fashioned theory has actually won out against the newfangled one.

What is the old-fashioned theory of planet formation?

The old-fashioned idea is the nebular hypothesis of Pierre-Simon Laplace (1749–1827) and Immanuel Kant (1724–1804). When a star forms, it's surrounded by a spinning disk of gas and dust, and planets form within the disk. Because the disk is largely circular, planets end up in circular orbits. Because there's more raw material for planet building in the more distant reaches of the disk, where things like water ice can condense and give you the building blocks of planets, gas-giant planets should be farther away from the star. Where there are fewer volatiles that condense, where there are heavier elements like silicon and iron, is where you should get terrestrial planets. After about 10 million years, the sun burns off what's left of the gas disk. And that's why the solar system is the way it is.

That's the old-fashioned way of looking at things. Nowadays, it's still basically that—just version 2.0. We can take the original

An artist's rendering of a gas-giant exoplanet orbiting a so-called subgiant star. The imagined planet has a ring and moon system similar to Saturn and Jupiter. As techniques improve in the future, astronomers may soon be able to detect rings and moons around exoplanets.



story up until the gas disk goes away. Maybe the planets start off in those nice circular orbits. But then they begin to gravitationally interact, tossing each other about, causing each other to undergo weird oscillations and inclinations. After that whole dance is done, the survivors are left on tilted, eccentric orbits that sometimes bring them very close to their star. There's much to that story that's yet to be understood, but I'm really excited about that. I'm glad that this is not a closed case, because I'm really enjoying this research. It's more fun when there are more open questions—at least for an observer. If you're a theorist it's not so much fun.

What about this field is exciting?

It gets me out of bed every morning. I literally can't wait to see the latest data. It happened to me just yesterday. I was observing remotely in the basement of Cahill until my collaborators relieved me at about 3 a.m., since I had a full workday the next day and needed to sleep. I went to bed at about 3:30, expecting to sleep until 10:30. But I woke up at 7:30 and started thinking, you know, we just observed this new system we found and it's really wacky. It's a hot Jupiter around a type of star that's not supposed to have any hot Jupiters. If this next observation falls on the predicted curve, and it's likely going to be very real, then I'm going to have to think about how to share this with everybody. I couldn't go back to sleep. I was bone-tired, but I was excited and hyped up, so I got up and started working on the paper.

I don't know if I would get that level of excitement if I were doing cosmology or if I were studying galaxies—not to say that those fields are not immensely important and have exciting results. I just see new things every day that nobody on Earth has ever seen. It's just really fun being in a field of astronomy that's in its infancy—and being in a place like Caltech where we have Keck access once a month and we can actually watch all this happen.

It's like you're a field biologist observing some sort of new species.

Yeah. What this reminds me of is when people started exploring the deep sea in submersibles, and they would go into these tiny little things with one-foot Plexiglas walls and a tiny viewing window, and descend three miles down and look out into the dark with the light and all of a sudden, there's some octopus-looking thing that nobody's ever seen before, or some angler fish that's totally unexpected. I remember watching a documentary recently where they went down to the bottom of the ocean and they found an undersea lake. It was just a lake of heavier, denser water sitting at the bottom of an ocean. No one expected that. I imagine those marine biologists are similar to me. After doing one of those runs where they go deep under the water, they come back up and try to go to sleep that night. They probably wake up early thinking, oh my God, I want to look at that sample again—that's amazing. I feel like we're doing the same thing out in space. We're going out into the solar neighborhood, where there are things that we thought were just familiar, things that we thought we understood. But just the wackiest stuff comes up—and it's sure keeping me busy.

Once we find more planets like our own, it'll further define our place and give us a better universal context for what it means to be human.

Can you give us a sense of how wacky these planets are?

In 2005, my collaborator, Josh Winn, and I started measuring the degree of alignment of planets, using an ancient technique now applied to the brand-new field of exoplanets. We didn't really know what to expect, but Josh would say to me every time we'd go to the telescope, "Tonight's the night we find a retrograde planet." I would chuckle and say, that would be awesome. But it would also be awesome to find a new car in front of my house. Finding a retrograde planet would be awesome and wonderful, and I wouldn't give it back if we happened to find one. But I didn't in my heart of hearts expect we would do it. Then, four years later, I was on my way up to use the eight-meter Subaru telescope to measure the spin-orbit angle of a planetary system. He wasn't able to join us on the run, but he sent me an email, and at the bottom he wrote, "Tonight's the night we find a retrograde planet." As usual, I said that'd be great. And that was the night we found a retrograde planet. That was another one of those weeks where I wasn't getting much sleep because this was amazing—absolutely amazing.

It's like going out on safari and saying today's the day we're going to find a blue lion. And then you do find one, and you go, what is this? It must be a joke! That might be the level of wackiness I would attach to it. There might be some visionaries out there who totally expected a retrograde planet. But to actually find one—that was just weird.

What got you interested in science in general?

Stephen Hawking. *A Brief History of Time*—it changed my life. It's kind of clichéd. Half of all physicists are in physics because of that book. That's definitely what got me. Other popular-physics books after that sealed the deal. I was an engineer when I started off as an undergrad, doing aerospace and mechanical engineering. But it wasn't as interesting as discovering things about the universe.

But it all started in college. I can't say that I was one of those kids who begged their dad to buy them a telescope and then used it in their backyards. I had zero interest in astronomy until late in my college career. I was the kid who stayed inside and played with his Legos instead of the kid who went outside and explored under rocks. I was an engineer.

Were there any "aha!" moments during your career?

I remember more of the moments when I realized I wasn't cut out for engineering. In college, I did an internship with John Deere in Iowa. I realized that my crowning achievement for that summer internship was developing a new ladder for a front-end loader for the operator to climb up on. I just thought, "There's got to be more to this." If I was going to be sitting around figuring out very complicated things, then I wanted something that's more meaningful outside the company where I work. Some people are fine with that. I'm glad there are tons of people making bridges and building airplanes for us. But it wasn't for me.

Has there been a highlight in your scientific career so far?

Yeah, definitely. When I found my first planet.

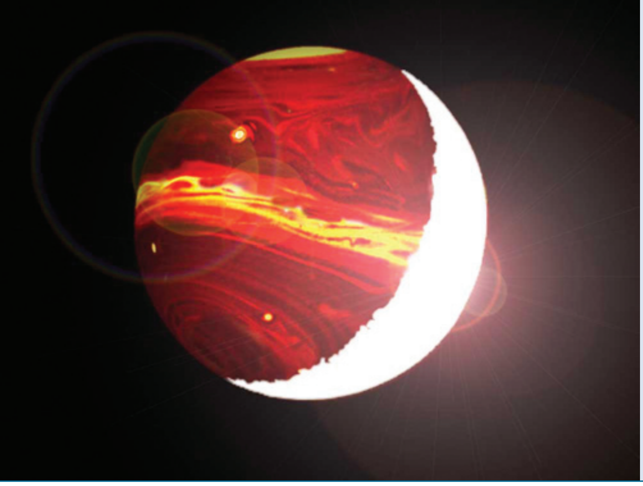
What was that like?

I couldn't sleep for a week. I had a whole bunch of data for my thesis, but I had not yet perfected the analysis software. There were some bugs that were making it very difficult for me to see signals clearly. When I finally got my code to work—that was an "aha!" moment. That was great. It was one of the first major analysis undertakings that I had done as a student. So suddenly I was able to see things clearly in my data. I went back to all the stars I had been observing for the past year and there was just a really clear signal that popped up for one of the stars. I looked at the velocities and fit a model to it, and there it was: my first planet. That was HD185269b. That was a real rush. It was the result of all the effort I put into it. That was the antimoment to that summer internship. That was the moment I realized, oh my God, I can do some really amazing stuff.

Where were you?

Lick Observatory, on a mountaintop. I had been observing for three or four days straight. It was great. I fixed the code, and immediately turned the telescope to get the star, which was in the process of setting. It was going to set in a few weeks after that. I remember that my friend was going to be on the telescope a week after I was, and I sent him detailed instructions about how to reach the star so he could grab a few more data points for me because it was going to be another three or four months before we could get more data. It all worked out great—great weather and everything.

I was using the smallest telescope, one that nobody wanted to use. I was also using a very old instrument that nobody else wanted to use either. So I had as much time as I wanted on the telescope—and I used a lot of time. Every night I'd go to dinner, walk from the diner to the telescope, open up the telescope, and do the calibration. Then I'd wait for the sun to dip down 12 degrees below the horizon and I'd get to the first target, and I'd walk across the sky observing one star after the next. Each observation yielded a velocity measurement, and those velocities



An artistic rendering of a so-called hot Jupiter on a three-day orbit around a Sun-like star. This image was based on atmospheric models of gas giants being bombarded by heat and radiation from its star.

over time gave the accelerations that those stars were experiencing. I would do that and repeat for four days straight.

Where do you see your work at Caltech in the near future?

Being here at Caltech is great. We have access to the world's largest optical telescope and a very high-precision radial velocity instrument—and they're giving me lots of time on them. I'm going to put it all to use. I have about four major projects going on. The sky's the limit at Caltech. I cannot do this anywhere else. I have these four projects to work on and see to completion in the next three years, probably. From there, it's exploring the two frontiers of exoplanets. The first consists of long-period planets, which you find by waiting. The longer we wait, the longer we observe a given star, the longer period we're able to detect. The other frontier is with low-mass planets. Those have very low Doppler amplitudes, so we have to push the precision of existing instruments and then build new instruments. My collaborators at Yale and Penn State and I have put a proposal to the NSF to build a new instrument at Palomar to use the five-meter telescope there. Once we get that project funded, that's going to keep people busy for the next 10 years. That'll be at the very frontier of this field—finding Earth-like planets, two or three Earth masses in the habitable zone of stars, where they could potentially have liquid water. That's going to be a major undertaking. It's going to require another factor-of-three increase in precision. It's going to require a lot of nights on the telescope, and it's going to take me right back to my thesis. But it's going to be great. I really enjoy it.

Is there any way to anticipate what we'll find?

Kepler, the space mission we're flying right now, is going to tell us what we're going to find. It's going to get the first view of what exists out there for the low-mass planets and longer-period orbits that we know today. It's blazing the trail, but it's doing it for stars that are very distant. We're going to be doing it for stars that are right next door. The first hints that are emerging from that mission are very promising.

Why should we care about finding exoplanets? They don't plug up oil spills.

Every astronomer goes through that existential crisis. You have to understand that our society as we know it today is shaped largely through a lot of different astrophysical discoveries. The fact that we know Earth orbits the sun came from astronomers 450 years ago. The work that we're doing today is going to impact our culture and our understanding of our place in the universe forever. It's going to happen slowly, but that's what we're in the business of doing. Exoplanets are really good for that because we live on a planet, and we are finding other planets. We're trying to understand the planet we live on—where did it come from? It's the ultimate origin story. We are coming out of the darkness from a couple hundred years ago and we're rubbing our eyes today, realizing that we are on a really small planet around a really average star in an unspectacular part of the galaxy, and we're learning our place in this whole universe. Once we find more planets like our own, it'll further define our place and give us a better universal context for what it means to be human. E&S

From top to bottom: graduate student Tim Morton, Johnson, postdoc Justin Crepp, and telescope operator Kajsa Peffer, in the control room of Palomar's Hale Telescope.

Addicted to Nicotine

The first pull on a cigarette should send you into convulsions. But instead, smoking can mellow you out and sharpen your mind. The series of unfortunate events by which nicotine works its magic in your brain is now becoming clear.

Despite his best efforts to quit, President Obama may still sneak a smoke from time to time. But can you blame him? He's got two wars, a sagging economy, and a cranky Congress to contend with; throw in a colossal gusher a mile deep in the Gulf of Mexico, and most people would be up to two packs a day. More than one billion people worldwide smoke regularly to enjoy its calming qualities and its mind-sharpening benefits; about five million people die from smoking-related diseases each year. But the fact that we can smoke at all without seizing up at each puff is a case of unlucky chemistry.

Nicotine—the relaxing yet addictive drug in tobacco—works its magic at the connections between the brain's nerve cells, where chemicals do the talking. At the heart of each connection is a gap called a synapse, where the electrical current traveling down a nerve fiber must somehow make the leap to the next cell. The neuron forwards its message by releasing molecules called neurotransmitters that spread within the void and bump into proteins on the surface of the receiving cell. There the neurotransmitters slip into pockets called binding sites, triggering a new electrical current that continues on its way. Nicotine sneaks into the synapses, usurping the binding sites and, in effect, sending its own messages.

The brain proteins that nicotine affects are nearly identical to a receptor protein on muscle cells that tells them to contract, but nicotine is essentially impotent at your muscle cells. "If you think about it, it must be true that these muscle proteins wouldn't be very sensitive to nicotine," says chemist Dennis Dougherty. "Because if they were, smoking would be intolerable—every puff would activate every muscle in your body." So Dougherty and biologist Henry Lester set out to discover why nicotine prefers brains over brawn.

Dougherty and Lester have been studying the chemistry of nerve signaling for almost

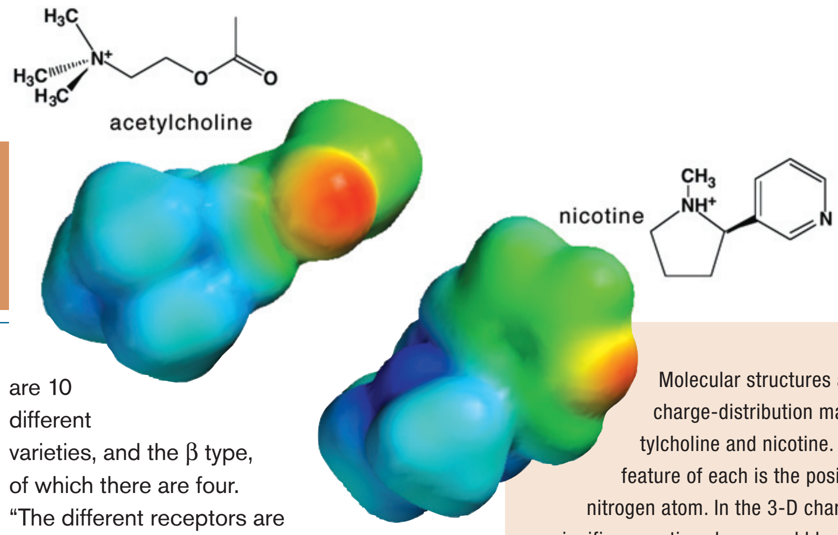
By Michael Torrice

two decades. (See "Smoke Gets in Your Brain," *E&S* 2002, No. 4.) Their work may help explain why smoking is addictive, and could enable the design of drugs to help you quit. Surprisingly, it might also lead to treatments for neurological diseases including Parkinson's and schizophrenia. There is no medical justification for smoking, but people who have smoked for 30 or more years are almost 50 percent less likely to develop Parkinson's disease than nonsmokers, and about 90 percent of schizophrenics smoke compared to 20 percent of the general population. It may be that nicotine helps counteract schizophrenia's attention and memory losses.

Nicotine hijacks a family of proteins called the nicotinic acetylcholine receptors, or nAChRs. Acetylcholine is a neurotransmitter-of-all-trades. In the brain, acetylcholine is involved in learning and memory, in maintaining alertness, and in the sensation of pleasure. Out in the rest of you, it's the intermediary between your nerve cells and your muscle cells, carrying commands across the synapse that separates them and setting your body in motion. So when you flex your pecs in the mirror and think to yourself, "Dang, I look good!" that's acetylcholine at work.

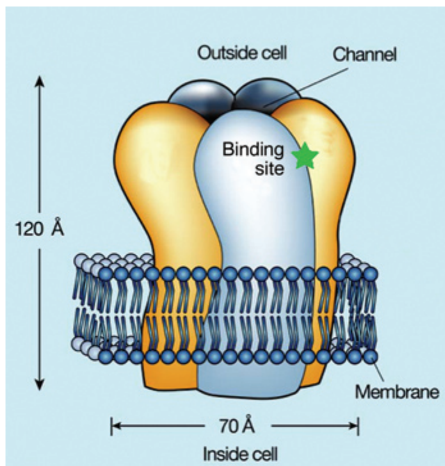
The nAChRs loosely resemble molars, with five roots and a crown, and sit embedded in a cell wall like teeth in a jawbone. Each tooth has a cavity on one side of the crown—the binding site, into which the acetylcholine molecule fits perfectly. The act of binding opens a pore that runs down the center of the tooth like a root canal, allowing ions to flow and create an electrical current.

There are more than 20 known types of nAChRs, each with a different assortment of five parts called subunits. Each subunit runs from a root up to the corresponding cusp, and together they surround the root-canal pore. The subunits, in turn, come in various kinds, including the α type, of which there are 10 different varieties, and the β type, of which there are four. "The different receptors are siblings—more closely related than cousins—but not identical twins," Dougherty says. "They all do the same thing—bind acetylcholine and then open the pore." But while binding acetylcholine brings nAChRs together as a family, their subtly different structures cause them to have distinct preferences when it comes to other molecules, such as nicotine. "It's a big family and each sibling has its unique personalities," Dougherty says. The brain's versions all consist of two or more α subunits, with β subunits filling out the remaining slots.



Molecular structures and surface charge-distribution maps for acetylcholine and nicotine. The important feature of each is the positively charged nitrogen atom. In the 3-D charge maps, red signifies negative charge and blue is positive. The same color scheme applies to the drawing on the opposite page, which shows a nicotine molecule being attracted to a molecule in the brain.

Adapted from Dougherty & Lester, *Nature* 411: 252 (2001) © Macmillan Publishers Ltd.



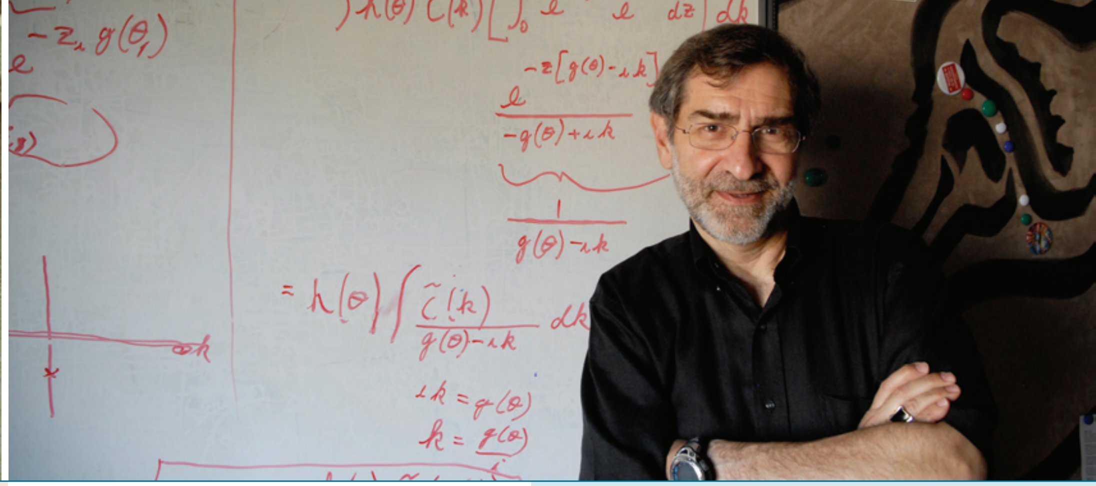
A nicotinic acetylcholine receptor sticks out of the cell membrane like a molar protruding from a jawbone. This one has two α units (yellow) and three β units (blue). The binding site is marked by the green star.

SO A CHEMIST WALKS INTO A BIOLOGY LAB . . .

Since nicotine and acetylcholine both fit into the same pocket, you'd think that they'd look pretty similar. They don't. Acetylcholine is a slender chain of carbon atoms, while nicotine is a stout fellow made of two bulky rings linked like a pair of handcuffs. But—and this is the key—both molecules have a nitrogen atom that can take on a positive charge.

A positively charged atom might seem like an unlikely key, since the protein molecule as a whole has no net charge. Normally, charged and uncharged molecules don't fraternize, avoiding one another like oil and water. But Dougherty's lab had spent years studying greasy molecules containing swirling clouds of electrons called π systems that impart regions of negative charge to otherwise neutral molecules. Opposites attract, and these π systems can bind to positively charged molecules through what's known as a cation-π interaction. (Chemists call positive charges "CAT-ions," pronouncing the first syllable like the house pet. For the full cation-π story, see "Sing a Song of Benzene, A Pocket Full of π," in the fall '94 issue of *E&S*.)

Meanwhile, neurobiologists at the Pasteur Institute, Columbia University, and elsewhere had found that the muscle receptor's



Above: Dennis Dougherty (left), the Hoag Professor of Chemistry, and Henry Lester, the Bren Professor of Biology.

nAChR binding site sits in the seam between two of the protein's subunits, both of which contribute amino acids to the pocket. Furthermore, five of these amino acids—three tyrosines and two tryptophans—were fingered as crucial for binding acetylcholine. The cation-π interaction was largely unknown in neurobiological circles, so it had been presumed that the crucial amino acids would be negatively charged in order to attract the acetylcholine molecule's positive charge. Tyrosine and tryptophan have no charge but they do have π systems, and in 1990 Dougherty and David Stauffer (PhD '89) proposed that a cation-π interaction might be at work.

However, studying simple substances in a lab flask is child's play compared to probing the workings of a large molecular machine such as the nAChR, whose 70,000 or so atoms make the job of trying to figure out which ones are the important ones nearly impossible. (By comparison, the previous molecules Dougherty had been working on contained about 100 atoms.) Chemists like to methodically alter their quarry an atom or two at a time and see how the molecule's behavior changes. "If there's a chlorine atom in a molecule, we want to know what it's there for," Dougherty says. Biologists, too, like to swap out parts and observe the effects. But since proteins are long chains of amino acids strung together, the biologists' unit of change is the amino acid, which can contain up to 27 atoms. To a chemist, this is like using a hatchet to dissect a stopwatch. And for someone accustomed to having the entire periodic table at their disposal, the 20 naturally occurring amino acids make for a seriously understocked parts inventory.

But there is a trick to making proteins more chemist-friendly—a neat bit of biological sleight-of-hand (see sidebar) devised by Peter Schultz (BS '79, PhD '84) in the late 1980s when he was a professor at UC Berkeley. The stratagem essentially inserts a new word into the DNA code book that commands the cell's protein-making machinery, allowing scientists to splice any molecule they like into a protein. The interloper, called an unnatural amino acid, merely has to have the standard amino-acid backbone in order to get strung into the chain.

In order to test Dougherty's hunch, graduate student Wenge Zhong (PhD '98) attempted to use this method to plant molecular informants on the muscle receptor. These amino-acid stoolies looked like ordinary tyrosines and tryptophans, but they were wearing wires—anywhere from one to four electron-hungry fluorine atoms that progressively siphoned the negative charge

Chemists and biologists both swap out parts of molecules to see how they work. But the biologists' unit of change is the amino acid, which can contain up to 27 atoms. To a chemist, this is like using a hatchet to dissect a stopwatch.

AN UNNATURAL TRICK

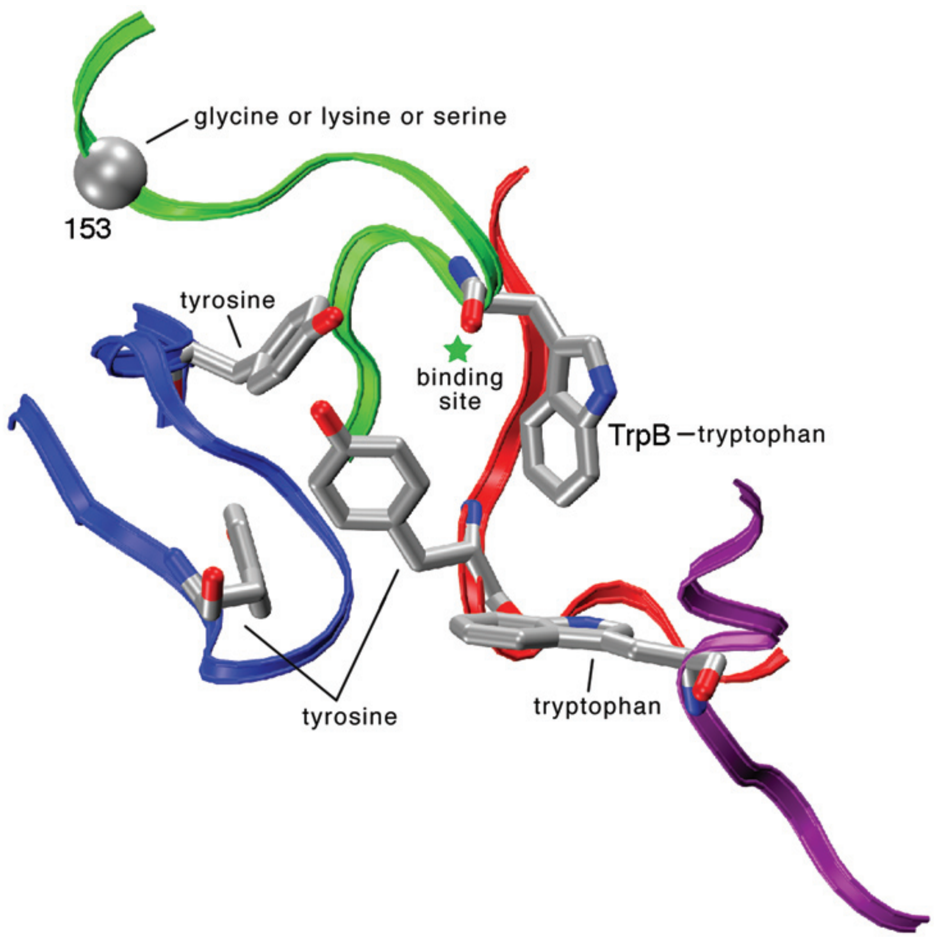
To sneak unnatural amino acids into proteins, you have to pull a fast one on the cell's protein-making machine. This machine, called the ribosome, synthesizes proteins by stringing amino acids together according to the instructions encoded in that protein's gene. The genetic alphabet has four letters, A, C, G, and T, that are combined into three-letter words, such as AAA for lysine and TCT for serine. As the ribosome reads the gene one word at a time, it decodes the words into amino acids with the help of adapter molecules called tRNAs. Each tRNA molecule recognizes one specific word, and hands the ribosome the corresponding amino acid to link onto the growing protein chain. But not every possible word in the genetic code translates into an amino acid, so an adapter molecule can be constructed to recognize a meaningless word and hand over an unnatural amino acid designed by the scientist.

In order to insert a custom-built amino acid into a protein chain, the researcher rewrites the protein's gene to include the new code word in the correct spot. This designer gene and the new tRNA adaptor molecule linked to the ersatz amino acid are injected into the cell in overwhelming quantities. Responding to the flood of work orders, as it were, the cell's ribosome starts executing its new instructions. When it reaches the magic word, the man-made adapter presents it with the unnatural amino acid. The imposter is dutifully inserted, and the ribosome happily continues translating the gene, unaware that it has just been conned. e&s

out of the π systems. With each loss of charge, that amino acid's π system would become less attractive to acetylcholine, making the neurotransmitter less likely to bind and the pore harder to open. So if the flow of ions through the pore tapered off as more fluorine atoms were crammed on to one of the five suspects, the cation-π interaction would be betrayed.

There was one small hitch in the plan, however. The receptor proteins need to be in their native environment in order to work properly, and Schultz's system for sneaking unnatural amino acids into proteins didn't work in nerve or muscle cells; it only worked in test tubes. So Lester and his biologists showed the chemists the next best thing: frog eggs. The South African clawed frog, *Xenopus laevis*, has been a neurobiology workhorse for decades because its unfertilized egg cells can be persuaded to sprout a crop of receptor proteins on their surfaces. And at one millimeter in diameter, the half-brown-half-white spheres are easy to inject with the receptor gene and Schultz's magical ingredients, and to gently impale on thin glass electrodes. Then all you have to do is spritz the cell with an acetylcholine solution and measure the current flow as the pores spring open. At least, that was how it was supposed to go—in practice, the Dougherty and Lester groups had to substantially modify Schultz's procedure to get it to work in frog eggs. This proved to be time well spent, however, as the technique they came up with is now a standard tool.

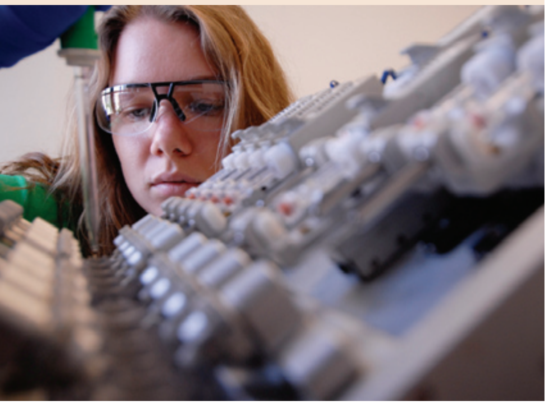
It took about two years to get results, but by 1998 Zhong had found that he couldn't pin anything on four of the five alleged perps. However, a tryptophan called TrpB—so named because it sits on the α subunit's "B" loop—was caught red-handed. With each fluorine atom added to the TrpB, the receptors grew steadily less responsive to acetylcholine. Surprisingly, though, the same set of experiments with nicotine showed

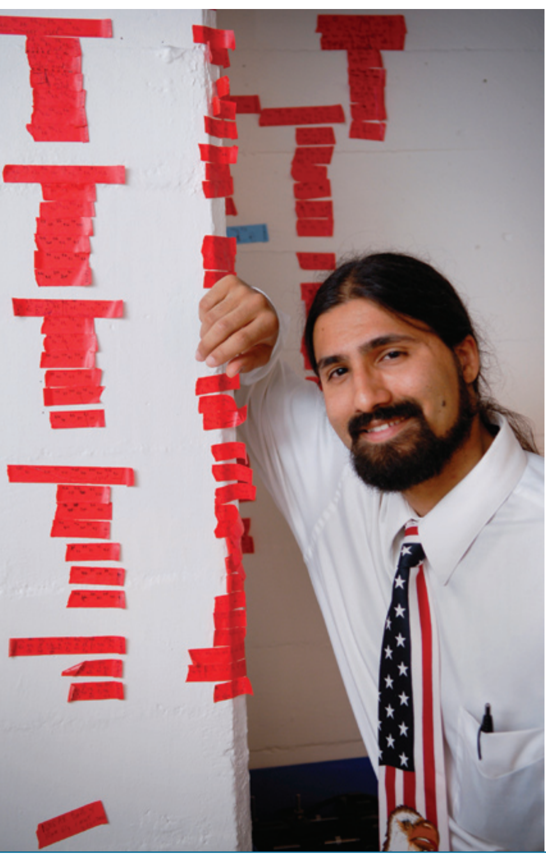


The nicotinic acetylcholine receptor's binding site is made up of four loops of protein. Five amino acids are critical for binding—a tyrosine in the "A" loop (the red ribbon), a tryptophan in the "B" loop (green), two tyrosines in the "C" loop (blue) and a tryptophan in the "D" loop (purple). When the acetylcholine neurotransmitter or the nicotine interloper slips into the binding site (green star), the molecule is surrounded by five π systems—the hexagons or hexagon-pentagon combos shown in the gray tube renderings of the amino acids.

The gray sphere marks the location of the 153rd amino acid in the "B" loop. Different amino acids are found in this position, depending on which receptor protein is being examined. This difference would provide a critical clue to solving the mystery of nicotine's selectivity, as we shall see.

Below: Grad student Nyssa Puskar and the OpusXpress, a refrigerator-sized robot biologist that can test eight egg cells at once.
Bottom: On each piece of red tape is electrical-current data from nicotine receptors in the egg cells. Grad student Jai Shanata poses with his pelts, as it were.





no loss of function, no matter how many fluorine atoms the chemists sent in. No amino acid in the lineup seemed to have any affinity for nicotine, which would explain why it doesn't turn on the muscle nAChR.

GETTING INSIDE THE BRAIN

Having flexed his muscles, as it were, Dougherty was ready to hunt for a cation-π interaction in the brain. But there the trail went cold for seven years—although the frog eggs had willingly churned out the muscle nAChR, they refused to make brain receptors. This biological brush-off shouldn't be too surprising, because egg cells don't naturally produce such proteins. "We were grateful that *any* nicotinic receptor can be grown this way," Lester says. "It was only a minor misfortune that the most studyable was not the most interesting one."

It eventually turned out that a simple mutation along the root-canal pore—originally discovered in 2001 in unrelated studies by Cesar Labarca, a Member of the Professional Staff in Lester's lab—coaxed the egg cells to work. So in 2006, Dougherty's grad students Xinan Xiu (PhD '08), Nyssa Puskar, and Jai Shanata began work on a protein that Lester and others had shown to be nicotine's main target in the brain—a receptor called $\alpha4\beta2$ because of the two $\alpha4$ and three $\beta2$ subunits that sit around its central pore.

The grad students rounded up the usual suspects, as all members of the nAChR family have that same cluster of three tyrosines and two tryptophans in their binding sites. But now there were crime-scene photos: molecular snapshots of a related protein found in snails (taken by Titia Sixma of the Netherlands Cancer Institute and others) had revealed that the five amino acids are arranged so that their π systems act as the four sides and bottom of what Dougherty calls the "binding box."

Technology had marched on, too. Zhong had measured the electrical currents in his muscle-receptor experiments one egg cell at a time. Getting the goods on a single fluorine substitution in one amino acid meant grilling several cells—a process that took hours. But in 2003, Dougherty and Lester jointly bought a machine about the size of a refrigerator laid on its side that automates this tedious process by sweating eight cells at once. Each cell sits in solitary confinement in its own well, impaled on its glass electrode. A robotic arm with eight nozzles sucks up a solution of acetylcholine or nicotine, zooms over to the line of wells, hovers, and squirts the liquid onto the eggs, repeating the process for increasing concentrations of the drug. "In 30 minutes, you can tell whether you have created either a gain-of-function mutation or a loss-of-function mutation," Puskar says.

Not surprisingly, acetylcholine latched onto the π system belonging to the brain protein's TrpB. But now the nicotine data mirrored the acetylcholine data: each additional fluorine produced a harder-to-activate receptor. This newfound cation-π interaction presumably explains nicotine's hundredfold greater potency at brain nAChRs compared to the muscle receptor. "It just makes sense," Puskar says. "The brain receptor has to have an interaction that doesn't exist in the muscle receptor. If smokers had this cation-π interaction in their muscles, they'd all be paralyzed."

SIBLING DIFFERENCES

But the five amino acids in the binding box are exactly the same in the muscle receptor, the $\alpha4\beta2$ receptor, and every other nAChR sibling. "At this level, they're identical twins," Dougherty says. "So this raises a fascinating question. We have two dozen different acetylcholine receptors with noticeably different pharmacologies. What's

“The receptor has 3,000 amino acids, but by changing just one—the right one—we can make the muscle receptor look like a brain receptor.”

happening?” He adds drily, “We had to think outside the box to find a solution to this puzzle.” The binding box is held in shape by four loops of protein. Would changing amino acids elsewhere on these loops make a difference?

The chemists started scouring the neurobiology literature and found a spot four amino acids away from the critical TrpB that sparked their curiosity. In the muscle receptor, a small, simple amino acid called glycine sits in this position. But in $\alpha 4\beta 2$ and other nAChR receptors sensitive to nicotine, the glycine's spot is occupied by a much bigger amino acid called lysine.

The final clue came from work at the Mayo Clinic in Rochester, Minnesota. In 1982, Andrew Engel published a study of a group of patients with a rare genetic disorder that caused their muscles to waste away, leading to labored breathing, progressive clumsiness, and other problems. Engel suggested that their muscle nAChR was hypersensitive to acetylcholine: the receptor had a hair trigger and stayed active for much longer than normal. In 1995, his colleague Steven Sine discovered that the hypersensitivity was due to a mutation that replaced that glycine with a medium-sized amino acid named serine. Furthermore, the neuron's $\alpha 4\beta 2$ receptor is more sensitive to acetylcholine than the muscle receptor, so, in some ways, this mutation caused the patients' muscle receptor to become more “brainlike.”

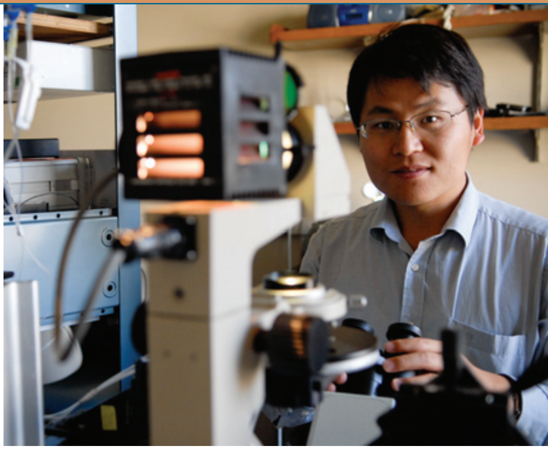
When Puskar, Xiu, and Shanata swapped in a lysine for that glycine in the muscle receptor and retried the experiments that had flopped seven years earlier, they hit the jackpot—a muscle receptor with an affinity for nicotine. “The receptor has 3,000 amino acids, but by changing just one—the right one—we can make the muscle receptor look like a brain receptor,” Dougherty says.

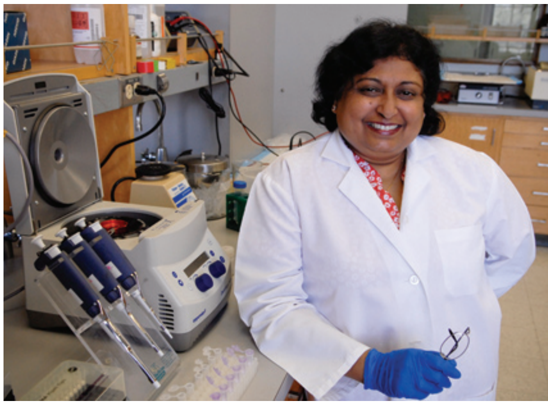
It's not clear exactly how the muscle receptor changes, but Dougherty thinks that the mutation reshapes the binding box. The slender acetylcholine molecule fits into both the muscle and the $\alpha 4\beta 2$ boxes, but the bulkier nicotine can't. Somehow, putting a lysine at this critical spot in the muscle receptor pries open the box enough so that nicotine can squeeze in.

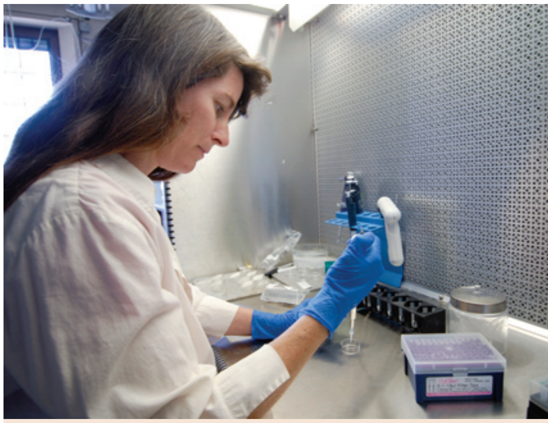
NICOTINE'S UNLUCKY BIOLOGY

While Dougherty and his chemists have focused on what nicotine does on the cell surface, Lester and his biologists have peered inside the cell to pinpoint what makes the drug so addictive. Nicotine, like many drugs, is adept at slipping through cell membranes. The cation-π interaction that lures nicotine to the receptor depends on the nicotine molecule having a positive charge. But nicotine as a neutral molecule is oily, and by shedding its charge it can then easily infiltrate the palisade of greasy molecules in the cell membrane. Once safely inside, the nicotine molecule can snag a passing proton and become positively charged again, ready to bind to receptors in the cell's protein nursery and seize control. “The binding that the cation-π experiments discovered takes over,” Lester says. “This very strong interaction allows nicotine to play three roles in a story that my lab is just starting to understand.”

In a 2007 collaboration with researchers at the University of Pennsylvania and the University of Colorado at Boulder, Lester postdocs Raad Nashmi and Cheng Xiao and staff biologists Purnima Deshpande and Sheri McKinney created mice with fluorescent $\alpha 4\beta 2$ receptors, and watched the results as the rodents received nicotine doses equivalent to a person smoking two to three packs per day. Over the course of a week or two, the mice sprouted significantly more $\alpha 4\beta 2$ receptors in the midbrain, which processes rewards and is the seat of addiction. (Interestingly, Parkinson's disease causes some dopamine-producing nerve







From top: Postdoc Cheng Xiao, lab manager Purnima Deshpande, and Sheri McKinney work in Lester's lab.

cells within the midbrain to slowly die off.) When these cells were sprayed with nicotine, they fired about twice as often as cells from "nonsmoking" mice. "We're essentially taking movies of events inside the neurons during the first minutes, hours, and days of nicotine addiction," Lester says.

It appears that nicotine acts like a chaperone, a matchmaker, and a traffic cop inside the cell—a combination of roles that maximizes the odds that each nAChR the cell produces will actually reach the cell's surface. As a chaperone, nicotine binds to nascent receptors' subunits as they are being synthesized, preventing them from being chewed up by the cell. The details are still being worked out, but "the simple idea is that nicotine stabilizes the receptor in a conformation that does not appeal to the cell's mechanisms for eliminating poorly folded proteins," says Lester. And, because the receptor's binding box is made from amino acids on two of the five subunits, nicotine the matchmaker expedites their assembly by binding to the two free-floating halves of the box and holding them in the correct orientation. This gives the remaining three subunits something firm to latch onto, helping them fall into place. And finally, as the cell transports the newly assembled nAChRs to the neuron's surface, the nicotine molecules bound to the receptors could act like a police escort, once again protecting them from the cell's protein-digesting machinery. "Scientists don't understand how chronic drug use leads to addiction—in any type of addiction," Lester says. "But the hypothesis that chaperoning, matchmaking, and traffic direction are necessary and sufficient is our lab's best bet at the moment."

Lester and colleagues at the University of Colorado at Boulder, and the drug company Targacept, have a grant from the National Institutes of Health to find drugs to help people quit smoking. The collaboration, which also includes Lester's postdoc Ryan Drenan, has set its sights on another nAChR family member that seems to consist of an $\alpha 4$, an $\alpha 6$, a $\beta 3$, and two $\beta 2$ subunits. "These $\alpha 4\alpha 6\beta 2\beta 3$ receptors seem to be as strongly activated by nicotine as the $\alpha 4\beta 2$ receptors, but they seem less susceptible to nicotine's roles as a chaperone, matchmaker, or traffic cop," Lester says. He thinks that if smokers took an $\alpha 4\alpha 6\beta 2\beta 3$-specific drug, they'd experience some of nicotine's benefits—soothed nerves or focused minds—without the addiction. Popping that pill might slowly wean them off cigarettes.

Lester's lab is also looking for branches on the nAChR family tree that might make good targets for drugs to treat neurological diseases such as Parkinson's and schizophrenia. The experiments are beginning to show how chaperoning and matchmaking might underlie the protective effects against Parkinson's disease.

In addition, another collaboration with the University of Colorado at Denver is working on the $\alpha 7$ receptor, which nicotine also hits. Schizophrenics' neurons don't produce as many $\alpha 7$ receptors as healthy people do, and some scientists think that when these patients smoke to assuage their chaotic minds, they get relief by sparking the few $\alpha 7$ receptors that they do have into overdrive. So a drug that acted like nicotine, without its addictive properties, could make a better schizophrenia treatment.

Dougherty and Lester plan to continue to explore the nAChRs' sibling differences. But Dougherty points out that this portfolio of pharmacological preferences is, in itself, a side effect: "Remember all of these proteins evolved to respond to acetylcholine, not ever to nicotine or to any other drug." Evolution had some reason to tweak the muscle receptor's binding site, but it definitely wasn't to block nicotine. So, when you take a drag on a Camel and feel your scattered mind come into focus, the fact that you might be worrying—if you're so inclined—about lung cancer or heart disease rather than about instant paralysis is, as Dougherty says, "just bad luck." E&S

Dennis Dougherty, the Hoag Professor of Chemistry, started his academic career as a physical organic chemist after receiving his PhD in chemistry at Princeton University in 1978. He's been on the faculty at Caltech since 1979—first studying small organic molecules in flasks, and now investigating large brain proteins in frog eggs.

Henry Lester, the Bren Professor of Biology, studied biophysics at Rockefeller University and received his PhD in 1971. After spending two years as a researcher at the Pasteur Institute in France, he joined Caltech in 1973. He and Dougherty have been collaborating since 1992 on projects involving unnatural amino acids. ***The current work is supported by grants from the National Institutes of Health, the California Tobacco-Related Disease Research Program, the Michael J. Fox Foundation, the Gordon and Betty Moore Foundation, and Louis Fletcher (BS '56, MS '57).***

Michael Torrice (PhD '09) was a graduate student of Dougherty's. He is now an assistant editor at **Chemical & Engineering News*****.***

This article was edited by Douglas L. Smith.

Left: Andrew Lange, Frances Arnold, and their sons, James, William, and Joseph, on vacation during a five-day camel trek in the Sinai Desert in 2004.

Below: If the universe is closed, then parallel lines converge and features on the CMB will look magnified (bottom left). If the cosmos is saddle-shaped, parallel lines diverge and the patterns will appear smaller (bottom right). BOOMERanG showed that the universe is almost completely flat.

ANDREW LANGE

1957-2010

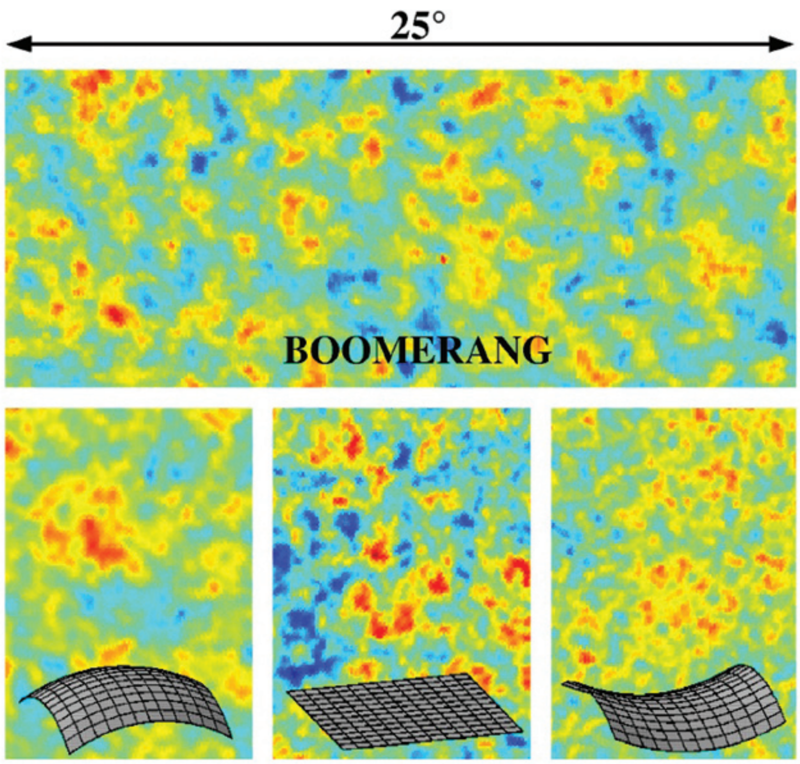
Noted cosmologist Andrew Lange, the Goldberger Professor of Physics at Caltech and a senior research scientist at the Jet Propulsion Laboratory, took his own life on January 22, 2010, shortly after stepping down as chair of the division of physics, math and astronomy. At a packed memorial service in Beckman Auditorium on May 7, friends and colleagues—interchangeable terms, in Lange's case—paid tribute to the prolific instrument builder and consummate experimentalist whose balloon-borne BOOMERanG instrument, on a 10-day circumpolar flight around Antarctica, provided the first evidence that the "inflationary theory" was correct and that the universe was flat. The experiment also independently showed that the cosmos was mostly made up not only of dark matter but something even weirder called dark energy. (For the full story of the BOOMERanG experiment, see Lange's "An Ultrasound Portrait of the Embryonic Universe," in *E&S* 2000, No. 3.)

The BOOMERanG results were announced on April 26, 2000, which Michael Turner (BS '71) of the University of Chicago called "the day cosmology changed." He noted that "BOOMERanG appeared on the front page of the *New York Times* twice," and that the second occasion "was a first for science—the first time that a spherical harmonic power spectrum has ever appeared above the fold." (This second article also included results from Chicago's own experiment, DASI, which had a number of Caltech and JPL collaborators.)

A "flat" universe—meaning that parallel lines really *are* parallel out to infinity—was the biggest prediction, and therefore easiest to prove wrong. The prediction arose from "this crazy idea theorists had that the universe underwent inflation" after the Big Bang, Turner said, "expanding in a jiffy—a jiffy, for those of you who are not familiar with the term, is 10^{-35} seconds." In that instant, the universe grew more than it has ever since, from perhaps one ten-billionth the size of a proton to about the diameter of a grapefruit at speeds well in excess of the speed of light.

Testing this prediction meant mapping temperature fluctuations in the Cosmic Microwave Background (CMB), the afterglow of the Big Bang, over the entire sky in unprecedented detail. BOOMERanG achieved a thermal sensitivity of one hundred-millionth of a kelvin and a spatial resolution of about one-third of the size of the full moon, thanks to a kind of heat detector called a spiderweb bolometer, invented at UC Berkeley while Lange was on the faculty there. In fact, one of his grad students, Jamie Bock, designed and built the first ones.

Lange earned his BA in physics from Princeton in 1980 and then spent 14 years at Berkeley—half his academic career, from grad student through postdoc to professor—before coming to Caltech in 1994. Paul Richards, his thesis advisor and, later, faculty colleague, recalled that Lange was fond of telling how, on a road trip in the summer of '79, "he stopped in cold at the Berkeley as-



A youthful-looking Lange in his dorm room on the upper floor of Witherspoon Hall at Princeton University during his junior year (1977-1978).

tronomy department and asked about research. The secretary took one look at him, decided he was a high school student, and brushed him off with the statement that only the most brilliant scholars should even consider applying to the Berkeley astronomy department. So Andrew wandered over to the physics department, where he got a better reception, and he left with a handful of graduate-school application papers." After Lange was admitted, Richards continued, his undergraduate advisor, David Wilkinson, "wrote to me to say that Andrew had written the best senior thesis that he had seen in 15 years, and that I should get him into the laboratory as quickly as possible. The Andrew Lange who walked into my office, or maybe rode his motorbike into my office, exhibited great enthusiasm, great confidence and remarkable people skills. It would obviously be fun to work with him. He wanted to work on the most difficult and most important project that I could offer, with the idea that this way, he could learn the most."

Lange had a thing for fast cars and motorcycles.

That first year as a graduate student set Lange's future course. He learned to make bolometers, working on a balloon-borne infrared mapping experiment with Steve McBride. "And by the time the balloon was ready to fly," said Richards, "Andrew had not only completed his coursework, but he had learned a tremendous amount about ballooning, about bolometers, and quite a bit about what happens to you if you pull too many all-nighters before a balloon flight."

Lange's own thesis project flew on a series of Japanese sounding rockets. On the first flight, the experiment's cover didn't open, and he had to settle for a description of the instrument for his PhD thesis, which he earned in 1987. He had better luck on the next attempt, publishing a major paper the following year describing an unexpected hump in the CMB spectrum that became known as the "submillimeter excess"—an exciting result that might have marked the birth of the very first stars, had it not later turned out to be spurious. "It was a difficult experiment," says Richards. Yet, "somehow, no matter how tough things got, he had people smiling."

In 1992, Richards and his protégé Lange entered into a collaboration with Francisco Melchiorri of the University of Rome and *his* protégé, Paolo de Bernardis, for a new series of balloon experiments. The Italians would be in charge of the telescopes, the cryogenics, and the gondolas the instruments rode in, and the Americans were responsible for the bolometers and the electronics. This evolved into MAXIMA, led by Richards, and BOOMERanG, led by Lange and de Bernardis. MAXIMA, which had the better cryogenics and higher sensitivity, was designed for relatively short flights from NASA's National Scientific Balloon Facilities (NSBFs) in the United States.; the less-sensitive BOOMERanG would compensate by staying aloft longer, operating from the NSBF at McMurdo Station, Antarctica.

Recalled de Bernardis, "After one year of detailed instrument design, we presented our parallel proposals in Italy and in the U.S. And they were both rejected. But, as Andrew stated, 'a new experiment of this kind is like falling in love. There's no way anybody can stop it.'" They tried again the following year, and the funding gods smiled. Meanwhile, Lange and his grad student Jamie Bock were in the process of moving to Caltech and JPL, respectively, where the spiderweb bolometers would be perfected.

The move to Caltech coincided with Lange's marriage to Frances Arnold, now the Dickinson Professor of Chemical Engineering, Bioengineering, and Biochemistry, in March 1994. (The pair had met in Monterey, California, in 1992, when both were Packard Fellows. They separated in 2007.) The universe around us may have no center, but the blended family's three sons, James, William, and Joseph, were the center of Lange's universe. "Andrew was a very private person," de Bernardis said. "He loved his family immensely, and used any opportunity to spend more time with his sons. He carefully avoided mixing personal life and work. I treasured the rare occasions when we spoke about our lives and our expectations for the

Although the CMB variations are faint, they are quite large. Here, in a more suitably Antarctic color scheme, the CMB has been inserted to scale behind BOOMERanG's launch preparations.

future of our sons."

Lange had taken a sabbatical from Berkeley as a visiting associate at Caltech in 1993. Recalls JPL Director Charles Elachi (MS '69, PhD '71), "At that time I was in charge of space science and instruments, and I got this call from campus saying, 'There's this young researcher that we're trying to attract—do you mind spending some time with him?' So he shows up in his usual way with a big smile—very charming—and I was so taken by his vision, by his enthusiasm, that in half an hour he got a promise out of me that if he comes to Caltech, I'll fund his research. And then he left, and I said, 'How in the heck am I going to come up with all that money?' I called Virendra Sarohia [MS '71, PhD '75] at the microdevices lab, and I said, 'I have good news and bad news. The good news is I met this great scientist, the most inspiring I've ever had a discussion with, and we really need to bring him to Caltech. The bad news is, you have to figure out how to come up with $400 K.'"

BOOMERanG's maiden flight in the summer of 1997 at the NSBF in Palestine, Texas, went even worse than Lange's first rocket adventure. The flight was aborted just after launch, recalled de Bernardis, and "[we] found our payload, lying on its side, in the middle of a muddy pond used to water cattle near Waco [more than 90 miles from the launch site]. I still have the rubber boots." After several hours of recovery work in cow-scented muck, "the cryostat was still cold, and five bolometers out of the six were still alive. So we decided that we wanted to fly it again as soon as possible, and Andrew used all of his charisma" to convince the NSBF to give them a second chance. But with the balloon campaign ending in two weeks, "the following ten days were a nightmare. We had to open all the electronic and mechanical systems, clean out mud, frogs, and unidentified filth, dry them and test everything extensively. We made it, and ten days later, BOOMERanG was flown. We had our first data set, and we qualified for the 1998 Antarctic campaign."

Lange's managerial style on the project brought out the best in people, de Bernardis said. "I appreciated his capacity to listen, and to take every important decision in open meetings or teleconferences, where everybody could just say what they thought. And he was really able to instill enthusiasm in the younger collaborators."

In the process, Lange raised the bar for Caltech-JPL collaborations. "He saw how to bring the science of Caltech and the technology of JPL together better than anybody else I have known," Elachi said. "He always used to stop at JPL as he was driving from his home in La Cañada down to Caltech. We have a grassy mall with a coffee stand right in front of the administration building, so I used to regularly see him sitting there, sipping his coffee." (As Lange remarked in a video clip of a JPL presentation from 2009 that was shown at the memorial, "My usual office hours are right out by the fountain early on Wednesday and Friday mornings.") "And then half hour later, I would see a group of students and JPL people sitting around him, discussing the research they were doing. He had this very casual, very pleasant, magic way of bringing the two institutions together to do great things."

Many of Lange's grad students and postdocs would become JPL employees, and several JPL staff members came down to Caltech to get their PhDs with him. Lange mentored some 20 grad students, one of whom was William Jones (PhD '05), now a professor of physics at Princeton. Jones recalled making a trip to California to shop for grad schools, and meeting Lange "in his nearly windowless office in the crumbling basement of West Bridge. That meeting was electric. It was warm. And it was inspiring. If you're familiar with the basement of West Bridge, you'll know that these words do not at all describe the place. But it was my first experience with the extraordinary charisma of the man, and like many others who came before and after me, it left little doubt in my mind where I wanted to spend the rest of my graduate career.

"Andrew himself was driven by success and he expected as much of his students," Jones continued. "When you were able to bring an interesting result to Andrew, or evidence of progress that truly excited him, his enthusiasm was infectious. It came with a sense of validation that kept us striving to come back with more. When his expectations were not met, the contrast was stark. Andrew had little patience when he felt that you weren't realizing your full potential. And he did let you know it. In that regard, the relationship between Andrew and his students was parental." This aspect of the relationship extended beyond work. "When Andrew would ask you how you were doing, he meant it. He wanted to know how *you* were doing."

Lange attributed his mentoring principles to David Wilkinson, his faculty advisor at Princeton, Jones said, and codified them as "Dave's Rules" for a memorial for Wilkinson, who died in 2002:

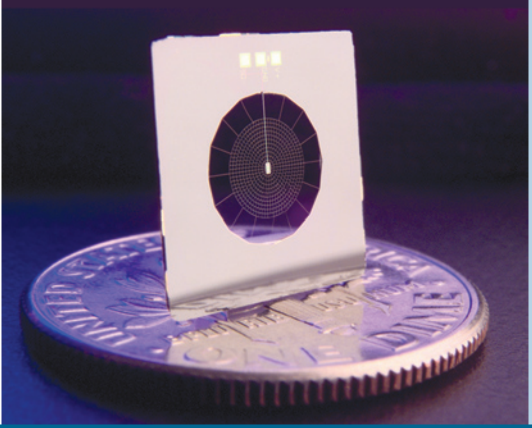
- Work on important problems—better to "fail" at something important than "succeed" at something unimportant.
- Make it look fun and easy—the students won't know any better until it's too late to turn back.
- Give the students lots of room—all of the survivors will be great.
- Keep an eye out for new technology—an important problem + great people + new technology = success.
- Keep it simple—you'll be able to move on to the next attempt more quickly.
- Be gracious—nurture everyone's potential.

In following Dave's Rules, Jones said, "Andrew encouraged his students to bite off a lot. But not more than they could chew, although perhaps sometimes they thought it was more than they could handle. The esprit de corps in the group, forged in the flames of the intense activity, was something he cared deeply about, and the enduring friendships among so many of his students are a testament to his success in this regard. Andrew, I think wisely, was not at all a micromanager. He set priorities and expectations, provided advice and resources, and then enjoyed watching his students flourish. Much of his genius, I think, was centered on identifying good people and good problems and getting them together. He nurtured everyone's potential. And that's *everyone*, from the students to the building staff. Andrew took an interest in every individual that participated in the life of the lab. Supportive, inspiring, and driven, I can say for myself and for his former students that we all owe Andrew a deep debt of gratitude."

Abigail Crites (BS '06), now a graduate student in astronomy and astrophysics at the University of Chicago, worked in Lange's lab from the beginning of her prefrosh summer. She said, "Andrew had this way of seeing something in a person, and taking a risk to give them an opportunity to flourish because of what he saw. When I came to him that summer asking for a job, I merely had the idea that physics was cool. It turned into four years of undergraduate research, and that's what really turned me into a scientist." Lange thought hard about the projects he assigned her, Crites said, picking tasks commensurate with her developing abilities and taking every opportunity to use her results to teach her new physics. "I did things as simple as peeling old aluminum tape off the BOOMERanG cryostat with Brendan [Crill, a JPL scientist], to as complicated as doing my senior thesis on testing sapphire for half-wave plate development."

Crites also commented on Lange's involvement with students beyond the lab. A rocky freshman year academically had her on the verge of leaving Caltech, but Lange "reassured me that I was just having a typical Caltech experience. So I decided to stay, but I still had my parents to tackle. They wanted me to move. Andrew made a personal phone call to my lovingly overprotective father and told him that he really believed that this was the best place for me, and the best place

Lange at McMurdo Station in Anarctica working on BOOMERanG in December 1998.



A spiderweb bolometer, with a dime for scale. The freestanding mesh is etched from the silicon nitride film deposited on the silicon wafer that supports it, and is then coated with thin gold film. The CMB photons are absorbed by the metal, and a highly sensitive thermometer, sitting like a spider in the middle of the web, registers the infinitesimal temperature rise. The web design catches nearly all the CMB radiation while using as little material as possible—the mesh only covers about 5 percent of the interior area—to avoid collecting cosmic rays and to minimize heat capacity. The spiderweb was originally designed for BOOMERanG to use in Antarctica, where the high incidence of cosmic-ray collisions was a concern.

for my career as a scientist. He went out on a limb for me, after only knowing me nine months, telling my father that he was going to be there to support me. And he really was. He was there to support me for the rest of my time at Caltech. If I ever had a hero, it was Andrew. Even four years into my time at Caltech, I approached each of our meetings with this nervous excitement. It just never wore off."

Lange had a hand in 22 different CMB projects, according to a list compiled by Turner, who said "I was astonished to find out that Andrew had his name on 300 papers. Now for a theorist, that's not uncommon, because we just make stuff up. But he actually *built* things and measured things."

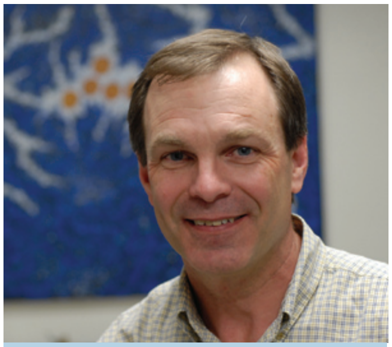
Lange's culminating contribution to cosmology is 52 bolometers, designed and developed at JPL. They are now flying in the High Frequency Instrument on Planck, a European Space Agency mission launched in May 2009. Planck will look for the so-called "B mode" polarization of the CMB that is supposed to be produced by Einstein's long-sought, but as yet undiscovered, gravity waves. "To good approximation, JPL got to do the most fun, sexy parts of this mission," Lange said in that same JPL video clip. "Now that the detectors are alive on orbit, they are officially obsolete, and we've moved on to the next technology. There's a very interesting tension: at any given time in this business, what you can do on an orbital mission and what you can do with a small experiment put together by six graduate students at the south pole has been pretty comparable. And the reason is the graduate students have technology that's ten years younger."

And there will be new technology to come. At Lange's instigation, JPL has embarked on a major initiative under Bock to build very-large-format superconducting arrays that will represent as big a jump over the spiderwebs as they did over preceding designs. Says Elachi, "[Lange's] vision was to fly these arrays on a future mission to measure the polarization. With his enthusiasm, I didn't need to be convinced. I knew that when Andy is enthusiastic about something, he's going to make some major new discoveries. That will be the legacy he has left for us at JPL."

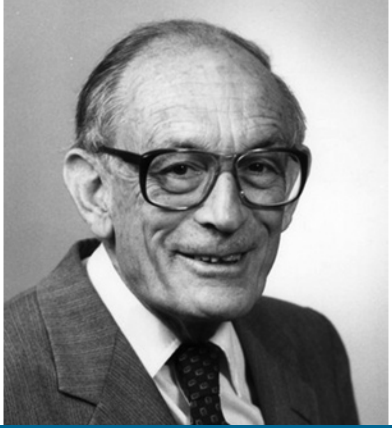
Caltech's president, Jean-Lou Chameau, announced at the memorial that Lange had been posthumously awarded NASA's Exceptional Public Service Medal—its highest award for nongovernment employees—for his leadership in JPL's contribution to the French-built High Frequency Instrument, and for the development of its detector technology. (Earlier notable awards include the 2009 Dan David Prize, which he shared with de Bernardis and Richards, and the 2006 Balzan Prize, which he shared with de Bernardis.)

Chameau called Lange's death "a personal tragedy for Andrew's fans, his family, and his colleagues here at Caltech and in the world," and "a universal tragedy, because Andrew will not be able to continue his vital work—universal both in the field of study of our universe, and in the scope of potential achievements that may now be lost," adding that "It must inspire us to recommit, as a community, to do whatever we can to help people suffering from depression. The entire Caltech community was shocked by Andrew's death and we will all truly miss his presence on campus, and the feeling he engendered that anything was possible."

John Mather, who shared the Physics Nobel in 1996 for his CMB work on the COBE satellite, and who had known Lange since the latter had taken a year off from Princeton to work in his lab at NASA's Goddard Space Flight Center, was unable to attend the memorial but sent a letter that concluded: "I remember Andy as a very young, extraordinarily bright, extremely imaginative, and thoughtful scientist. I also knew him as a person with exceptional empathy for others, who could make an instantaneous connection on an emotional level. . . . I think he would want us all to take good care of our own selves, and perhaps have a little more faith that things would work out fine in the end. I only wish he had been able to have that faith for himself. He was much loved." —*DS*



Reminiscences and pictures of Lange can be found on this public Facebook page:
http://www.facebook.com/group.php?gid=297676654852&v=wall
Or, you can search for "Andrew Lange" on Facebook.



HANS W. LIEPMANN

1914-2009

Hans Wolfgang Liepmann was known for his wit and infectious enthusiasm that inspired generations of students. As a leading researcher in fluid mechanics, Liepmann was the Theodore von Kármán Professor of Aeronautics, Emeritus, and was the third director of Caltech's Graduate Aeronautical Laboratories (GALCIT) from 1972 to 1985. He died on June 24, 2009, at the age of 94.

"When all is said and done, his greatest contribution to Caltech and to the scientific area was the enthusiasm he brought to his work, the confidence he gave younger folks convincing them how important they were and what their work meant in the context of the aeronautical world," said Frank Marble, the Hayman Professor of Mechanical Engineering and Professor of Jet Propulsion, Emeritus, in his oral history. At Liepmann's memorial, held on January 23, 2010, John Cummings (BS '69, MS '70, PhD '73) recalled his experience as a sophomore in a thermodynamics course taught by Liepmann: "Hans gave us a test and none of us did very well. And instead of coming back and being frustrated with us, Hans said, 'I haven't taught you well. Let's try again.' I just can't imagine another Caltech professor ever saying something like that." When it came to publishing, Liepmann didn't care to have his name attached to every paper, Cummings said. "Hans didn't have a big ego," he recounted. "He wouldn't allow me to list him as a coauthor on two publications from my thesis work . . . It was, as he said, my work, not his—very different from many professors."

In his own oral history, Liepmann explained why he always emphasized teaching. "I consider teaching more important," he said. "That's really our main goal in life, if we take the professorship seriously. And also, I think, it has the more lasting influence. Whether you like it or not, most of your startling papers are going to be footnotes in handbooks in the not-too-distant future, and that goes for everybody. . . . But the teaching, the passing on of a certain style and approach to science, and also to knowledge, in a sense; that is, in my opinion, a more challenging and also more rewarding business."

Liepmann genuinely cared for his students, always taking the time to talk to each of them and entertain everyone when he threw parties at his big white house overlooking the Rose Bowl. "If there was one thing I remembered about Hans besides being a great teacher, it was his ability to host a party," Cummings said. Years later, after Cummings graduated from Caltech, he would return with his wife and spend time with Liepmann, who always welcomed them with coffee and snacks.

He was always an advocate for the students, and they invited him to be Caltech's commencement speaker in 1982. "I think the undergraduates are really mistreated here," he said in his oral history. "I'm amazed that they don't make more noise, because they are overloaded. . . . They are always behind, always overworked, and then you get this famous burn-out; they suddenly want to take a leave. I do not think we should cater only to the best-prepared and brightest guys, but take into account the possibly deeper, but certainly slower-moving ones."

Born in 1914 in Berlin, Liepmann grew up during World War I. His father was a physician and his grandfather was a professor of surgery, and because of family tradition, he was put into a classical school, where he was forced to study Greek and Latin—even though he had decided early on that he wanted to study science. "I had a terribly tough time in school," he said. "I only kept going because I always thought, 'Boy, when I get out of here! I have to get out, I have to go to the university, and then I will do physics.'"

Just a month after Hitler came to power, his family left Germany in 1933 for Istanbul. There, Liepmann got his wish and studied physics, mathematics, astronomy, and mechanics. After graduate studies at the University of Zürich, he came to Caltech in 1939 to work with Theodore von Kármán, who recruited him after he, having downed a few too many beers at his PhD party, inexplicably blurted out that he wanted to study "hydrodynamics." Up until that party, he never drank, he said.

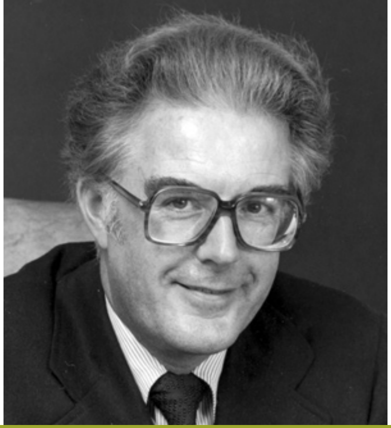
Liepmann hardly spoke English when he first came to the United States, which he initially tried to avoid because of its reputation as a country filled with "very rich people, very poor people, and gangsters." Of course, he discovered that "it was pure nonsense," and he soon mastered the language, although his distinctive accent stuck, becoming an endearing quality to those around him. "They loved his very strong Berlin accent," said Donald Cohen, Powell Professor of

Applied Mathematics, Emeritus. "They loved it so much that they mimicked it. Hans knew it, but he didn't mind."

Friends and colleagues fondly remembered his endless string of anecdotes and his wit. Colleague Robert Liebeck told one story that took place at the cafeteria, where Bill Se–ars (PhD '38) turned a blind corner and almost bumped into Liepmann, who was carrying a tray. "My God, I almost hit you," Sears said. Without missing a beat, Liepmann answered, "I told you not to call me that in public." According to Von Kármán Professor of Aeronautics, Emeritus, Anatol Roshko (MS '47, PhD '52), he was also known for his penchant for "the friendly insult, of which he was a master."

Roshko added that he was never politically correct. "He disliked bombast and self-importance, and here his agility with a polite insult often came in handy."

Liepmann inspired and encouraged generations of students, but his message to the class of 1982 is applicable to us all: "Remember that there is an outside world to see and enjoy. Add a fourth dimension: to know, to understand, to do—and to dream." —*MW* e&s



OBITUARIES

R. DAVID MIDDLEBROOK

1929-2010

R. David Middlebrook, emeritus professor of electrical engineering, died on April 16. He was 80.

Middlebrook passed away at his home with family by his side. Born in 1929, he was raised in Newcastle, England, and came to the United States in 1952 on the Queen Mary.

Middlebrook wrote a pioneering transistor textbook that included mathematical models to help engineers use transistors in their circuit designs; a later book focused on differential amplifiers. In 1970, he founded the Caltech Power Electronics Group, which graduated 36 PhD students, many of whom are now leaders in the power electronics field.

A distinguished international lecturer, Middlebrook was particularly noted for presenting complex material in a simple, interesting, effective, and entertaining manner. He was especially interested in design-oriented circuit analysis and measurement techniques, and his Structured Analog Design course was attended by design engineers and managers from the United States, Canada, and Europe.

Middlebrook also taught in-house analog-design courses for more than 20 years, working with companies such as AT&T, Boeing, Ericsson, Hewlett Packard, Hughes Aircraft, IBM, Motorola, Philips, Tektronix, TRW, and many others.

He is well known for his Extra Element Theorem, which describes the effects of adding a single element to a circuit. This theorem and its variations are widely used in circuit design and measurements.

Middlebrook received his BA and MA degrees from the University of Cambridge, and his MS and PhD degrees from Stanford University. He joined Caltech as an assistant professor in 1955; he was named associate professor in 1958, and professor in 1965. He became emeritus in 1998.

In 1996, the Caltech student body recognized him as an outstanding educator with its Feynman Prize for Excellence in Teaching.

"For more than 40 years, Dr. Middlebrook taught his students a way of thinking, not just a body of knowledge," the award's citation noted. "[H]e demonstrated to thousands of delighted students how to simplify complex subjects and how to marry theory and experiment. He also taught them a lesson in scientific modesty, as he constantly adopted the best solutions generated by his students."

Middlebrook was a Life Fellow of the IEEE and a Fellow of the IEE (UK). In addition to the Feynman Prize, he was the recipient of the Franklin Institute's Edward Longstreth Medal, the IEEE's Millennium and Centennial medals and its William E. Newell Power Electronics Award, and the Award for Excellence in Teaching, presented by the Board of Directors of the Associated Students of the California Institute of Technology.

He leaves behind a wife, Val, sons John Garrison and Joe Middler, daughter Trudy Wolsky, and grandchildren Chad and Teagan.—*JW* e&s

EDWIN S. MUNGER

1921-2010

Edwin S. Munger, professor of geography, emeritus, died on June 15 at his home in Pasadena, California. He was 88.

Munger was a renowned specialist on Africa, particularly race and ethnic relations. In his dozens of trips to the continent, he visited every African country, even living there for a decade.

Born in La Grange, Illinois, Munger received his BS, MS, and PhD degrees from the University of Chicago. He was a visiting lecturer at Caltech throughout the 1950s before becoming professor of geography in 1961. He became professor emeritus in 1988.

Munger took his first trip to Africa in 1947—financed by his Army poker winnings—and his second in 1949 as the first Fulbright Fellow to Africa, attending Makerere University, Kampala, Uganda. He was an Institute of Current World Affairs (ICWA) fellow in Africa from 1950 to 1954, and from 1955 to 1961 was an American Universities Field Staff member, during which time he lived a year each in Ghana, Nigeria, Kenya, and South Africa, while at the same time serving on the faculty of the University of Chicago.

He was an evaluator for the Peace Corps in Uganda (1966) and Botswana (1967) and chairman of the U.S. State Department Evaluation Team in South Africa (1971).

"One of the joys of being a geographer is that the world is my oyster, world travel my most stimulating teacher," he said.

His passion for the region led to his founding of the African Studies Association and the U.S.–South African Leader Program, and later, he served as a board member of the South African Institute of Race Relations. For 14 years he served as president of the L.S.B. Leakey Foundation, working to increase scientific knowledge and public understanding of human origins and evolution. He was also instrumental in launching the foundation's Baldwin Fellowships, which have helped more than 40 Africans obtain advanced degrees in archaeology. In 1985, Munger founded the Cape of Good Hope Foundation to help mostly black universities in southern Africa, and subsequently sent more than $3 million worth of books to help those institutions. He edited the *Munger Africana Library Notes* (1969–1982) and amassed a library of over 60,000 volumes on sub-Saharan Africa, the largest private collection in the U.S., and a unique cultural resource.

He was president of the Pasadena Playhouse (1966) and one of the founders of Caltech's Friends of Beckman Auditorium.

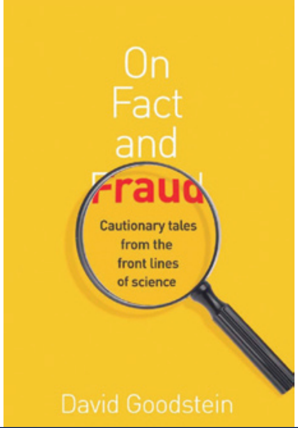
A respected teacher, Munger in 1976 received the top teaching prize given by Caltech's student body and in 1980 was made an honorary member of the Caltech Alumni Association. He continued to be a presence on the Caltech campus by joining notable faculty members at the campus faculty club—the Athenaeum—"round table," a lunchtime gathering of scientific leaders from various disciplines who meet to socialize and hold discussions of the highest order.

In 1993 he received the Alumni Citation Award for public service from the University of Chicago.

Later in life, he began collecting chess sets and at one point had amassed more than 400 ethnic chess sets, from the more than 250 countries and islands that he had visited.

Munger was a prolific author, producing numerous books on Africa.

Munger leaves behind his wife of 40 years, Ann Boyer Munger; daughter Betsy Owens from his first marriage with the late Elizabeth Nelson Munger; nephews Christopher and Roger; and nieces Jennifer, Trudie, and Sarah.—*JW* e&s



On Fact and Fraud: Cautionary Tales from the Front Lines of Science
by David Goodstein
Princeton University Press, 2010
184 pages, $22.95

BOOKS

On July 8 the third official U.K. report on what the press called "Climategate" was released. At issue were some 1,000 hacked emails from the Climatic Research Unit (CRU) at the University of East Anglia—a world leader in the field.

Among the stolen CRU emails one, by unit director Phil Jones, was identified as a smoking gun. In it Jones exulted over a "trick" by which proxy data had been eliminated to protect the upward swerve of his colleague Michael Mann's "hockey-stick graph"—something taken by Al Gore to prophesy a Venusian future for planet earth.

The July report was delivered by a long-retired civil servant, Sir Muir Russell. The CRU scientists, Sir Muir opined, had conducted their research with exemplary "rigour" and "honesty." Nonetheless, the tricky graph was "misleading." It was baffling. You expected it, of course, from car salesmen (and most politicians), but how could a scientist be "honest" and "misleading" at the same time?

David Goodstein's previous book, *Out of Gas*, went through many editions. When Princeton reprints *On Fact and Fraud* they should commission a supplementary chapter on East Anglia's nightmare. It's precisely the kind of case that fascinates Goodstein and that, as lawyers say, "makes good law."

On Fact and Fraud is founded on 40 years' research, 20 years' senior administration, and 10 years that Goodstein, Gilloon Distinguished Teaching and Service Professor and Professor of Physics and Applied Physics, Emeritus, and Caltech's vice provost from 1987 to 2007, has spent teaching a popular undergraduate course on scientific ethics with Caltech philosopher James Woodward. As the subtitle "Cautionary Tales from the Front Lines of Science" implies, the book is leavened not merely by long thinking on the subject but by laconic wit. (Anyone who has served on a committee with him will testify to David Goodstein's ability to enliven even the dreariest Friday afternoon.) It's a short book, easy to read, highly entertaining, and profoundly thought provoking.

On Fact and Fraud comprises not quite a dozen exemplary stories from various labs, several of them at the place Goodstein knows best. *E&S* readers will be familiar with the first tale—that of Robert A. Millikan's oil-drop experiments. Did Millikan, as has been alleged, cook the results that won him Caltech's first Nobel? After subtle exegesis, Goodstein concludes that it's a close call, but no, he did not. (Millikan, however, would have a harder time nowadays keeping his working materials under wraps for 50 years, with all those hackers poking their noses into his lab.)

Goodstein's second tale dates from the late 1980s, when a young Caltech postdoc, Vipin Kumar, was accused of faking a crucial figure in one of his papers. Goodstein—by now a kind of fraudfinder general at Caltech—was directly involved in the Institute's investigation, which "drew a distinction between research misconduct, which it concluded had occurred, and outright research fraud (involving deliberate intent to deceive), which Caltech believed had not happened."

Goodstein next considers the so-called Baltimore Case—a sorry business that, if nothing else, demonstrated the nonsense of federally appointed "swat teams" like the U.S. government's short-lived Office of Scientific Integrity (OSI). The case, which turned into a high-profile congressional hearing, was ultimately thrown out on appeal to the Department of Health and Human Services, which found that the OSI and its successor agency "had made errors that rendered their verdicts meaningless." (The name comes not from the Maryland city but from David Baltimore, Nobel laureate and then-president of Rockefeller University, where the fraud was alleged to have occurred. Baltimore himself was never accused of anything, but he leapt vigorously to the defense of his less-fortunate colleague.)

On the other hand, the saga of the cold fusion circus of 1989 might be called a success story for the scientific method. The extraordinary claims of several researchers to have achieved nuclear fusion in a tabletop apparatus were coolly taken apart by three Caltech scientists (Nate Lewis, Steve Koonin, and Charles Barnes) in a process that exemplified, as Goodstein shrewdly notes, how little rewarded, but vitally necessary, disproof is. Who ever got a Nobel Prize for showing it ain't necessarily so?

Physics, Goodstein chauvinistically claims, has less fraud than any of the other sciences, but Victor Ninov's 1999 "discovery" of a new element at Lawrence Berkeley National Laboratory (LBNL) is a shaming example from within Goodstein's own discipline. The damning verdict on Ninov was delivered by an LBNL committee headed by Caltech's own Rochus Vogt, whom Goodstein later invited as a guest lecturer to his ethics class.

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Goodstein ends each story with a brief "where are they now" that perhaps illuminates the role of contrition. For example, Kumar, whose claims that he "had just been trying to prepare a more compelling figure" and was "green and naive" were met with considerable skepticism, was nevertheless given the benefit of the doubt. After being dismissed from Caltech, "he served out a three-year banishment from National Institutes of Health funding" and has since resumed his career in science. The unrepentant Ninov, however, after dismissal from LBNL, "found a job as an adjunct professor of physics at the University of the Pacific, which apparently was unaware of his recent history. He is no longer listed on the faculty of that institution."

Above all, Goodstein is pragmatic. He rejects romantic ("inductivist," he calls them) myths that see the scientist as insulated from the real world. Scientists want to make careers for themselves; they want to be first with discoveries.

In the last analysis Goodstein, the consummate scientist, comes across as an advocate of humanism—odd as the term may seem. It's no accident that he cross-listed his immensely successful course with Caltech's humanities and social sciences division and has cotaught it with a philosopher. Goodstein's humanism expresses itself as a fundamental belief that scientific honesty is, ultimately, an ethical issue. Scientists, like Caltech's undergraduates, must live by an internalized honor code. It's a noble idea.

This, then, is the moral of David Goodstein's cautionary tales: be good; and if you can't be good, you'd better be very, very cautious.—*JS* e&s

This review was written by John Sutherland, who was on the faculty from 1984 to 1992 and was a visiting professor of literature, and then of English, until 2007. He is now a professor emeritus at University College London.

A MINE FOR DARK MATTER

In "A Mine for Dark Matter" in the Spring 2010 issue of E&S, we described the late Caltech astrophysicist Fritz Zwicky using a choice of words to which the Zwicky family strongly objected. They sent us this letter, which we publish exactly as received.

Dear Editor:

My grandfather, Fritz Zwicky, was a brilliant cosmologist and visionary who courageously forged into the unknown universe and discovered Dark Matter. His morphological methodology, Zwicky Box, allowed him to envision as yet unseen phenomena and realize those in this dimension. *Directed Intuition in Astronomy - "We shall be concerned here mainly with the prediction and visualization of the existence of as yet unknown bodies in cosmic space." (Zwicky xi).* I can appreciate the attention his historical accomplishments have garnered, Dark Matter, Supernovae, Gravitational Lensing, Sky Survey, and inventor of numerous jet propulsion prototypes holding patents in SQUID Solid Propellant, Thrust Motors with High Impulse, Two Piece Jet Thrust Motor, and Device and Method Jet Propulsion Through a Water Medium, that remain without parallel. The entire scientific intelligentsia, the renowned institutions in the world are spending enormous sums of money, including the greatest minds in science, have all thus far failed to explain Dark Matter 80 years after it was first identified.

My grandfather identified an extravaganza of precedent-setting observations that were not understood by many benighted ignoramus of his time. Therefore, he no doubt invoked great animosity by telling his colleagues that they were missing 99% of the universe, and that they were only looking at the dustbunnies in front of the door. No conductor wants to be told he has lost his caboose. Hence, there arose great resentment against his genius, and a resulting incessant campaign to suppress his work, extinguish the rightful credit due and transgress his memory upon his passing. Their voices remained remarkably silent during his lifetime.

It is becoming more clear to me that his shining superstar will always illuminate the heavens, and will never be surpassed by those of dimmer luminosity. As a scientific prophet, he will continue to suffer the literary assaults by self-serving authors, propelled by an embittered scientific establishment that continues the siege commensurate with their failure. His memory and work will be respected and accepted by a new generation that is not bound by fossilized paradigms no longer relevant in the sciences. He will be recognized and honored for his professional accomplishments on the world stage.

My grandfather's words identify the corrosive elements that he encountered on a continuum in the the scientific establishment.

"I first presented the possibility of neutron stars in my lectures on astrophysics at California Institute of Technology in spring of 1933, suggesting that they are formed by implosions from ordinary stars, with resulting liberation of tremendous energy. In November 1933 I present the theory of the origin of supernovae and of cosmic rays as being caused by the implosion of stars in to neutron stars." (xiv Zwicky).

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

"In contradiction to the professional astronomers, who ignored my views for thirty years, the reporters kept going strong on supernovae, neutron stars and cosmic rays. In the Los Angeles Times of January 19, 1934, there appeared an insert in one of the comic strips, entitled "Be Scientific with Ol'Doc Dabble" quoting me as having stated

"Cosmic rays are caused by exploding stars which burn with a fire equal to 100 million suns and then shrivel from 1/2 million miles diameters to little spheres 14 miles thick."

Says Prof. Fritz Zwicky, Swiss physicist (xv Zwicky).

Galaxies - Galaxies in order to achieve a fruitful meeting of the minds among astronomers who, at the present time seem to be highly confused on the subject of galaxies." (xv Zwicky).

"The scholar's mission requires the study and examination of unpopular ideas, of ideas considered abhorrent and even dangerous.

"Timidity must not lead the scholar to stand silent when he ought to speak.

"In matters of conscience and when he has the truth to proclaim the scholar has no obligation to be silent in the face of popular disapproval.

A Statement by the Association of American Universities 1953

Sincerely,

Christian Zwicky

SOME SUNLIGHT IN YOUR TANK

It is always nice to see a letter to the editor that I submitted to the Winter 2009 issue elicit a response from other readers. I would like to respond to Phelps Freeborn and Pierre Jungels, who submitted letters to the Spring 2010 issue.

Pierre Jungels:

I can't possibly forget that science and engineering never stand still. I spent my entire career in industry working on long-range research. I even briefly did some Fischer Tropsch chemistry following the Arab oil embargo in the 1970s.

It is not enough to make continuous improvements in your process, especially if you are starting out behind. You must also make improvements relative to *all* the other contenders.

Let me tell you a story illustrating the point. I coinvented a new process to make an organic compound called aniline. After a few weeks' work, an engineer interviewed me and evaluated the process's potential, giving us some challenging goals to meet. . . .

It took us 12 months to optimize a catalyst and then another six months to demonstrate its life in a pilot plant.

The existing process used a lot of energy to boil water. That was where our new process had a major advantage. There hadn't been any progress in 75 years, but once threatened by us upstarts, the people running the existing process learned how to boil water more cheaply in just those 18 months. When the two processes were compared again, we found that we no longer had any advantage over the existing one. . . .

Heat transfer is indeed a significant problem with the Fischer Tropsch reaction. A better reactor design would have an impact on the economics. . . .

If you have a spare afternoon and a small test reactor, I suggest you try passing your synthesis gas mixture over a zirconium oxide catalyst. I used Harshaw ZR-0304, 98 percent zirconia and 2 percent alumina. Although the alumina is added primarily to strengthen the pellets, it also adds acidic sites. If you get the same results that I did, you might ask your oil company friends how much more they would pay for the product from the zirconia catalyst than from a conventional iron-based material.

I wish you luck. May the best process win.

Phelps Freeborn:

It is not enough to consider only energy conversion. What's just as important is the investment required to accomplish that goal.

Sunlight is free, but energy from the sun is expensive because humanity does not yet know a cheap way to collect and store solar energy.

Consider the simple case of photovoltaic cells made out of silicon. They come in two varieties: amorphous and crystalline. The crystalline cells are much more efficient, but also much more expensive. The net result is that the two types have similar economics. Neither competes well with fossil fuels.

In my opinion, the winning process to replace fossil fuels will be the one that requires the least new investment. That will involve biology, not physics.

Frank Weigert [PhD '68]

Wilmington, DE e&s

Professor Sossina Haile and Beckman Professor of Chemistry Harry Gray work with young scholars (recent graduate student Lisa Cowan, PhD '07 pictured) to develop new materials and designs for sustainable-energy technologies.

Engineering & Science

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