California Institute of Technology

E&S

Engineering and Science

Volume LXX, Number 2, 2007

In This Issue

Some members of the Class of 2007 hang out on the bridge over Millikan Pond on graduation morning before marching in to a commencement that included the inauguration of Caltech president Jean-Lou Chameau. The featured speaker was Jared Diamond, professor of geography at UCLA and author of ***Guns, Germs, and Steel*** and, more recently, ***Collapse: How Societies Choose to Fail or Succeed.***

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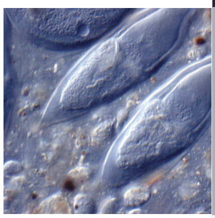

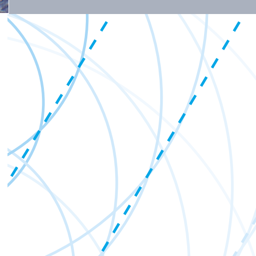

Departments

On the cover: A smoggy sunset amidst a phalanx of power lines frames the world's energy-consumption conundrum. If we can figure out how to store solar energy, we may be able to stabilize atmospheric carbon dioxide levels at only about twice what they are now.

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.

PICTURE CREDITS: Cover — Edison International; inside front cover, 2, 32, 38-39, 43 — Bob Paz; 5, 6, 42 — Caltech Archives; 6-7 — NASA, NASA/JPL/U. of Arizona; 9, 14, 21, 22, 34-35, 36, 40 — Doug Cummings; 17 — NASA; 25, 28 — Jared Leadbetter; 28 — Andreas Brune; 32 — Mercedes-Benz; 41 — Floyd Clark

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He's a Keeper!

Chameau gets Millikan's hood settled on his shoulders; otherwise, he's already settled in quite well, thank you very much.

After over nine months on the job, Caltech's eighth president, Jean-Lou Chameau, was inaugurated in a brief, simple ceremony at the start of Caltech's 113th annual commencement on June 8.

Chameau, who took office on September 1, 2006, was not in favor of a lavish affair that traditionally rivals a commencement in terms of pomp, circumstance, and cost, and desired instead to emphasize the students' accomplishments.

In the ceremony, overseen by Chairman of the Board of Trustees Kent Kresa, Robert Millikan's academic hood was placed on Chameau's shoulders by David Stevenson, the Van Osdol Professor of Planetary Science and chair of the Faculty Presidential Search Committee. While Millikan never accepted the title of president, he was the first administrative head of modern-day Caltech, and the passing of his hood to the new president has become an inaugural tradition. Chameau was then welcomed by Ricky Jones (BS '08), president of Ruddock House, who began by apologizing for non-Francophonic Techers' various manglings of his name—Shamu, Chamois, and, in cases of extreme confusion, Jean-Paul Revel [professor emeritus], and Jean-Luc Picard [starship captain]. Jones then spoke of Chameau's exhaustive efforts to get acquainted with faculty and students. He concluded with the story of Caltech's recent foray into the olive oil business (See *Caltech News*, 2007, No. 2 for details) and the role Chameau and his wife, Carol Carmichael, have played as part of their efforts to make the Caltech campus operate in a more sustainable manner, ending, "I'm certain that Jean-Lou will continue to encourage the growth of Caltech in ways we never thought imaginable, and to teach us to appreciate Caltech in ways we haven't before."

Chameau then addressed the audience, prefacing his remarks by introducing his wife and noting that "Carol and I are a team, and she is working very hard for Caltech." He went on to say that another university president had congratulated him on winning the lottery—"You have the best board of trustees in the country, the faculty is on a scale ranging from outstanding to genius, and you don't have to worry about a medical school or a football team!"

Chameau then offered some thoughts on Caltech's strategy for the future. He began by quoting Nobel Laureate Ahmed Zewail, the Pauling Professor of Chemical Physics and professor of physics, who said, "Caltech is a place where we dream with focus and freedom," adding "Caltech must be the place where people dream big; it must be the home of faculty and students who will do big things. The nation needs a place like Caltech—more now that ever." To do this, he said, "our commitment to advancing the frontiers of science and technology must include an interest in addressing the toughest challenges we face in society," using Caltech's small size to promote unlikely collaborations across disciplines that might develop, say, a clean energy source based on artificial photosynthesis. "As trustee Bill Davidow said, Caltech is a place where a few great scientists working together can make such 'long shots' happen."

Our small size, he said, should not only give students the ideal research university experience, but should also allow them to enter activities that might otherwise have been closed off to them. "The Caltech student experience should include an unusual menu of high-quality extracurricular programs in music, acting, competitive sports, journalism. . . . And even cooking! Caltech must be the preferred destination for young people who can make a difference, people who can do those big things that will change the world."

Which, of course, brought him to money. He called on Caltech to "develop the same level of excellence in its organization and administrative services as we already have in our academic programs. No university has done that yet. Caltech can do it." He also envisions a campus that is more energy efficient, cost efficient, and sustainable, not just for the savings that can be achieved but because "if we believe it's important to do research in energy and environmental science, we should believe in putting our discoveries into practice." He then noted the challenges of raising money in this day and age, and pledged to do his part to grow the endowment.

To this end he spoke of "friend-raising," noting that Caltech alumni, though wonderfully supportive, number fewer than 25,000—a downside of being small and selective. Thus, "we must cultivate more friends to compensate. My experience to date has been that there is lots of goodwill and admiration for Caltech. We need to leverage this goodwill to make many more friends—locally, nationally, and internationally." □—*DS*

Any Color You Like

If you shine a red laser pointer through a glass windowpane you don't expect it to come out blue on the other side, but with a much brighter beam it just might. At very high intensities light energy tends to combine and redistribute, and red light really can produce blue.

It normally takes brief bursts of megawatts of power to boost light into this high-intensity realm. But now Kerry Vahala (BS '80, MS '81, PhD '85), the Jenkins Professor of Information Science and Technology and professor of applied physics at Caltech, and postdoc Tal Carmon have found a way to do more with less, producing a continuous beam of visible light from an infrared source with less than a milliwatt of power.

At high intensities, light enters the regime of nonlinear optics. We usually notice nonlinearity when there gets to be enough of something to change its environment and rewrite the rules. For example, when a freeway is nearly empty and vehicles effectively have the road to themselves, traffic behaves in a certain way. Put twice as many cars on the road, and the traffic will still behave as if each car owns the road. The only difference is that the flow will double—a proportional, or linear, response. But once traffic nears peak capacity, the vehicles no longer act independently, and the flow becomes miserably nonlinear.

Similarly, light beams pass right through each other at the low intensities we typically encounter, because the photons that make up the beams can usually ignore the cross traffic. At high intensities, however, photons become much more likely to collide and reassemble into other photons—picture three Mini Coopers in dense traffic coalescing into an SUV. The big vehicles of the photon world lie at the higher-energy, or blue, end of the spectrum, with lower-energy photons appearing as red or even infrared light.

Nonlinear optics usually requires brief megawatt intensities, analogous to flooding the freeway with a sudden burst of traffic, but the Caltech researchers attained optical congestion with a much smaller flow by diverting traffic into a tiny no-exit roundabout.

Their traffic circle is a min-

Two adjacent rings can be made to emit different colors, depending on the frequency of the infrared light feeding each one.

From Carmon and Vahala, *Nature Physics*, vol. 3, June 2007, pp. 430–435. © 2007 Nature Publishing Group.

iscule glass donut, a microresonator smaller across than a human hair. It accumulates power so that a mere milliwatt of infrared light flowing outside the device can sustain an internal flow of 300 watts, a 300,000-fold amplification. Although the infrared light is essentially trapped, energy can still escape as visible light when three infrared photons combine into a single photon of tripled frequency.

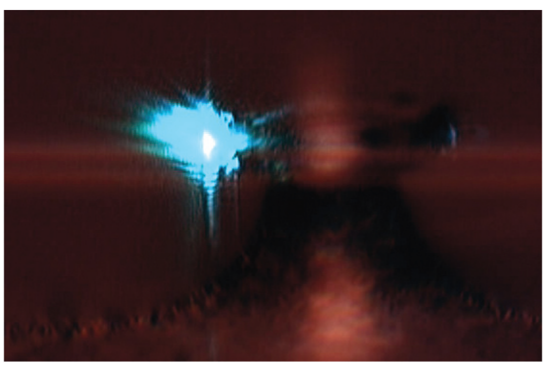
Usually researchers in infrared optics can't directly see their results. This time, Carmon says, "I just turned off the lights and you could see the effect immediately."

Although infrared light is invisible to human eyes, it is essential to modern telecommunications, flowing through millions of miles of optical fiber. Technology to produce, amplify, and otherwise manipulate near-infrared light is well developed and readily available.

"Our device has several important features," Vahala says. "First it triples the light frequency, and second, it works in a wide range of frequencies. This means full access to the entire visible spectrum, and likely ultraviolet. Right now there isn't a way of doing UV generation on a chip. Tunable ultraviolet—that's exciting." Coherent UV sources have applications in sensing and also in data storage, where, for example, the laser's wavelength determines the physical size of the information bit on a compact disk.

The microresonator is part of a promising approach for on-chip optical devices using the silica-on-silicon platform, which is compatible with the electronics of ordinary computer chips. Integrating optics and electronics on the same chip makes the device useful for lab-on-a-chip designs, and the ability to use established fabrication techniques makes large-scale, low-cost production possible.

This work, with Carmon as lead author, appeared in the June 2007 issue of *Nature Physics*. □—*JA*



From Carmon and Vahala, *Nature Physics*, vol. 3, June 2007, pp. 430–435. © 2007 Nature Publishing Group.

An end-on view of a beam of blue light coming out of the ring.

Mercury's Molten Core

Mercury, the solar system's smallest planet, had long been thought to have cooled and solidified ages ago. So scientists were astounded when, in consecutive flybys by JPL's Mariner 10 in 1974 and 1975, the planet gave inklings of a magnetic field, albeit a weak one—about 1 percent that of Earth. (Then again, Mercury is only 5 percent the mass of Earth.) This suggested the possibility of a molten core, but various measurements and models yielded an array of possible internal configurations with no conclusive evidence for fluid inside the planet—until now, says Cornell astronomy professor Jean-Luc Margot, lead author of a report published in the May 4 issue of the journal *Science*. The report shows that Mercury does indeed have a liquid center, although how big will only be determined by further observations.

The idea to examine the state of Mercury's core began brewing during Margot's O. K. Earl postdoctoral fellowship at Caltech, from 2001 to 2002, which, says Margot, "came with the freedom to investigate the science problems that I found interesting." Among them was a hypothesis—posed by physics professor emeritus Stan Peale of UC Santa Barbara, a coauthor on the paper—that the nature and extent of Mercury's core could be determined via observations from afar. Because Mercury is the closest planet to the sun, its surface temperature is too toasty for the spacecraft of today, so the scientists turned to radar astronomy. Margot began the work at Caltech by designing a way to test Peale's idea and by gathering preliminary data, and continued it at Cornell.

They applied a technique—derived from ideas first set forth in the 1960s and revived recently by coauthor Igor Holin of the Space Research Institute in Moscow—called the "speckle displacement effect," using JPL's 70-meter antenna at Goldstone, California; the Arecibo Observatory in Puerto Rico; and the Robert C. Byrd Green Bank Telescope in West Virginia. From 2002 to 2006, 21 different radar signals were beamed to the planet from Goldstone or Arecibo, and their echoes were received by two of the three antennas each time. Each echo had a unique speckled pattern, reflecting the planet's surface roughness, which swept across each receiver in turn like spots of light from a rotating disco ball, allowing Mercury's spin rate to be determined to within one part in 100,000. To make the measurements, the planet and the receiving antennas had to line up in a configuration that lasts only 20 seconds on any given day. "Everything had to happen within that 20-second time window," Margot says.

The team found tiny variations in Mercury's spin rate that could only be explained by the sun's gravitational influence on a planet that is part liquid. "We have a 95 percent confidence level in this conclusion," Margot says. The variations, called longitudinal librations, arise as the sun's gravity exerts varying torques on the planet's slightly asymmetrical shape. In addition to measuring Mercury's spin rate, the authors also made a vastly improved measurement of the alignment of the planet's axis of rotation, showing that Mercury's spin axis is almost perpendicular to the plane of its rotation around the sun.

Goldstone observations were enabled by coauthors Raymond Jurgens, senior JPL engineer, and Martin Slade, head of the Goldstone Solar System Radar and JPL's Planetary Radar Group Supervisor. □—*EN*

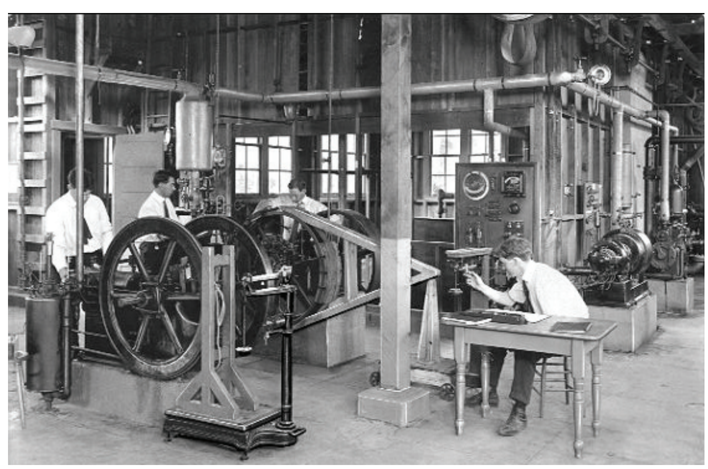
Mechanical Engineering Celebrates its Centennial

Mechanical Engineering at Caltech turns 100 this year, and a party called "It's All About ME" was held on March 30 and 31. "I was in rather a quandary trying to organize it," laughs Chris Brennen, the Hayman Professor of Mechanical Engineering. "The alumni only like to hear about the past, and the faculty only like to hear about the future. I got complaints from both groups, so I must have done a good job." The hundred or so returning alums got a dose of history, but they were also treated to lectures and posters on current research, and talks by alumni on new directions in the field. There was also live entertainment, as it were, in the form of a restaged ME 72 design competition and a demonstration of Alice, Caltech's self-driving entry in the upcoming DARPA Urban Challenge in which robot vehicles will try to navigate themselves through 60 miles of city streets.

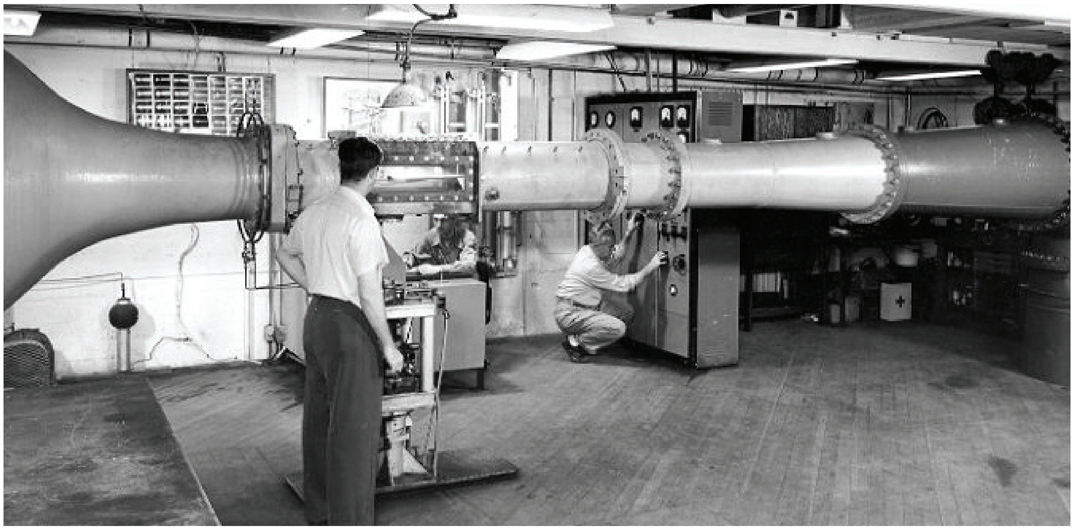
In 1907, the then-Throop Polytechnic Institute was in a cluster of buildings in downtown Pasadena, at the intersection of Fair Oaks Avenue and Chestnut Street. The ME department's start was modest enough—the only degree offered in engineering was electrical, and the sole ME course, Theoretical and Applied Mechanics (lab and lecture), was listed as Math 13. But as the catalog for 1907–1908 stated, "It is also the purpose of the Institute to extend the work along these lines as demand for it arises." Arise it did—the 1910–1911 catalog listed two faculty associates in mechanical engineering and, in the tradition of the low student-to-faculty ratio for which Caltech remains famous, two juniors pursuing mechanical engineering degrees. By the time Throop changed its name to the California Institute of Technology in 1920, the ranks had grown to three professors, an instructor, and 81 students.

But it was Caltech's Pump Lab, founded in the early 1930s by Robert Knapp (PhD '29) and instrumental in developing the equipment needed to bring water from the Colorado River to a thirsty Los Angeles, that "marked the transition from the department being a technical school that trained engineers to inventing the engineering of the future," says Brennen.

This transition was complete by World War II, when Knapp and colleagues turned their attention to broader issues of hydrodynamics. Chief among these was the noisy cavitation caused by the high-speed propellers on submarines that alerted their prey to their presence, and gave their positions away to the destroyers waiting above. And on the other side of the battle, torpedoes dropped from airplanes tended to take off in any old direction upon hitting the water. The problem was solved by stabilizing fins invented at Caltech and tested first in the lab and then at full scale up at Morris Dam, in the San Gabriel River canyon above nearby Azusa. "The remarkable body of literature generated in those years is

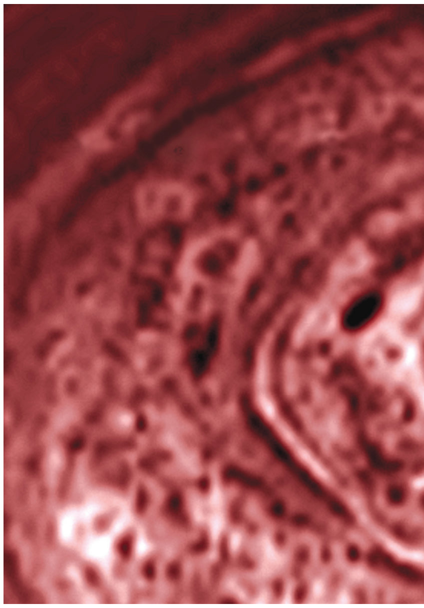


Throop Polytechnic's Hydraulics and Mechanical Engineering Lab in the early 1910s. From left: Raymond Catland, Charles Wilcox, Harold Black, and Robert Bultman, all BS ME '15.



Left: Caltech's Hydrodynamics Laboratory's high-speed water tunnel, designed by Knapp, seen in the mid-1940s.

Above: Two ME alumni speakers, Garrett Reisman (MS '92, PhD '97) and Robert Behnken (MS '93, PhD '97), seen at their day jobs training for their upcoming Space Shuttle flight to the International Space Station in February 2008. Reisman gets to stay there, replacing ESA astronaut Léopold Ehyarts.



still sought out—50-year-old reports that are still read by people working in high-speed flow," says Brennen. "And during the centennial, most of the people that wrote those reports were here."

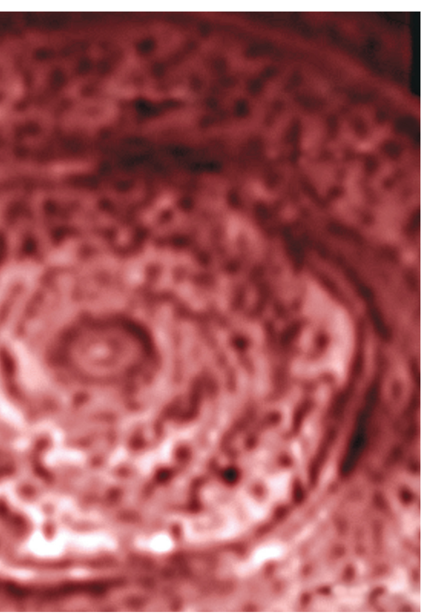
The study of high-speed flows burgeoned in the 1950s and '60s, with the development of the instruments and equipment needed to observe them. "The million-frame-per-second camera designs developed by Albert Ellis (BS '43, MS '47, PhD '53), for example, are still in use today to observe fractures as well as flows," Brennen remarks. [For more on cavitation and high-speed cameras, see *E&S* 2007, No. 1.] These instruments, in turn, allowed various faculty members to do basic analyses of how combustion chambers, gas turbines, and jet engines work, leading to the much more efficient designs of today. Similar strides were made in analyzing flows in which more than one state of matter is present, such as the solid-liquid jumble found in a mudslide, the solid-gas (granular) flow of coal in a power plant, or the three-phase flows of solid, liquid, and gas in a core meltdown in a nuclear reactor.

All of this analysis meant a lot of new mathematical techniques were needed. Various faculty members rose to the challenge, devising methods for grappling with random and nonlinear phenomena. A good example is the development of the mathematics underlying nonlinear elasticity, which refers to a situation where the force required to bend something is not proportional to the amount it bends. This includes the behavior of rubber or anything else that's soft and squishy, as well as such exotica as the shape-memory alloys used, for example, in stents to hold open clogged blood vessels. Roughly half of these are made of a metal that, at body temperature, opens up from a collapsed, easily insertable form into a hollow tube.

An influx of young faculty in the 1980s took the department in a host of new directions, says Brennen. "Mechanical Engineering has broadened tremendously—thin films, robotics, computational mechanics, control and dynamical systems, bioengineering, nano- and microsystems. The centennial was a celebration of that diversification." The professorial faculty now numbers 17, and the department is ranked third in the nation among graduate programs by *U.S. News & World Report* and fourth in worldwide impact by the Institute for Scientific Information's Science Citation Index.

The department's next century will undoubtedly bring more new directions, says Brennen. "Engineers take ideas and turn them into practical solutions. Energy R&D is a big component of ME today—producing devices to make energy or use it more efficiently. But there are other threads. The mechanics of biological systems and biologically compatible systems will be big in the future. So will the engineering of complex systems—how do you engineer, design, and fabricate complex electromechanical systems from cars to spacecraft?" Not surprisingly, the Caltech-JPL connection was a recurring theme throughout the celebration. "JPL has gone a long way in inventing the organizational techniques needed to do this successfully. In my view, despite all the consumer-product effects one hears about, this is by far the biggest spin-off from JPL and from NASA, and the continuing development of these complex management and control methodologies is likely to be a major part of mechanical engineering in the future." □—*DS*

Below: A hexagon around Saturn's north pole, glimpsed by the Voyagers in the early '80s, is still there. The feature, near 78° north latitude, was shot by Cassini in infrared light in October 2006. The structure extends at least down to the 3-bar pressure level, some 75 kilometers below the visible cloud tops, and may be a standing wave.



Medea's Antimalarial Mosquitoes

Malaria infects more than half a billion people every year, and kills more than one million, mostly children. Despite decades of effort, no effective vaccine exists for the disease, caused by single-celled *Plasmodium parasites*. The parasites are transmitted to humans via the bite of infected mosquitoes. One way to stop malaria is to make the mosquitoes themselves fight the disease. This can be tricky, however, because bugs carrying the disease-resistance genes are likely to be less reproductively fit than their wild counterparts, and thus less able to spread their genes. But now Caltech Associate Professor of Biology Bruce Hay, postdoc Chun-Hong Chen, and colleagues have developed a way to make such genes spread themselves quickly throughout an insect population.

"People who live in areas affected by malaria and other mosquito-borne diseases are bitten often," says Hay, "so there will be little benefit unless most of the local mosquito population is disease resistant."

The technique exploits a maternal-effect dominant embryonic arrest—or Medea—genetic element, a particularly spiteful selfish genetic element. (In Greek mythology, Medea killed her own children to revenge herself upon her unfaithful husband.) "Selfish genetic elements, single genes or clusters of genes, are more successful than your average gene at passing themselves from generation to generation," says Chen, even if their presence makes an organism less fit. "Our idea was to create a selfish genetic element that could be linked with a specific cargo, the disease-resistance gene, as a way of rapidly carrying this gene through the population."

Medea elements were first described in 1992 by Richard Beeman and colleagues at Kansas State University, who found one in the common flour beetle *Tribolium castaneum*. The version developed in this project uses two linked genes. One gene, the "poison," is turned on in the mother and produces a piece of small noncoding RNA, or microRNA, that prevents a protein known as myd88, which is crucial for embryonic development, from being made. The second gene, the "antidote," codes for a microRNA-insensitive version of the gene that produces myd88. Since all of the mother's egg cells will contain the poison microRNA, only the fertilized eggs that get the antidote from either parent will survive.

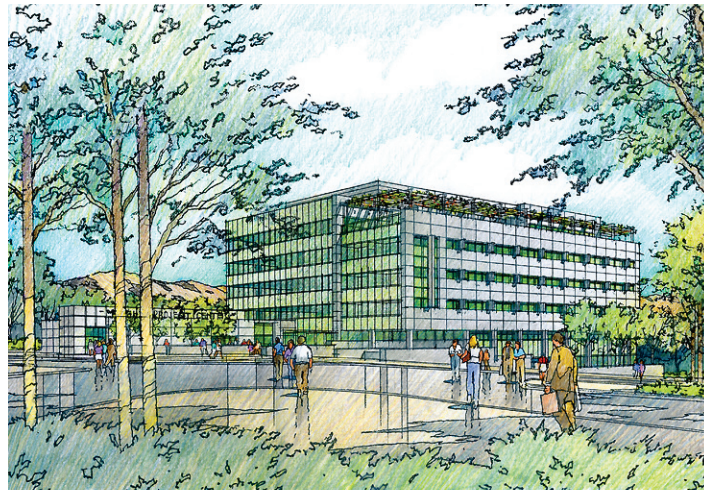
Fruit flies carrying this synthetic Medea element spread quickly throughout a laboratory population of wild-type flies. After just a few generations, all of the flies in the population carried at least one copy of Medea. "To our knowledge, this work represents the first de novo synthesis of a selfish genetic element able to drive itself into a population," says Hay. "It provides proof of principle that, at least in a highly controlled laboratory experiment, we can change the genetic makeup of a population." The team now plans to use the technique to transmit a real payload—a disease-resistance gene—into the mosquito. "There is a real possibility that disease transmission can be suppressed in an environmentally friendly way," Hay continues. "The mosquitoes will still be there, but with one or two tiny genetic changes that make them unable to transmit these dreadful diseases."

Even mosquitoes can only breed so fast, and in order for this approach to work, about 10 percent of the local population needs to contain the Medea element. "So it has to be introduced into the population reasonably frequently, which is very doable," says Hay. "In the '70s when people were doing biological mosquito control, they would breed mosquitoes in factories, and they would sort out the males and sterilize them with radiation. They were releasing millions of sterile mosquitoes every day. You *really* didn't want to be trapped in that factory overnight."

A paper describing the work appeared in the April

27 issue of *Science*, with Chen as the lead author. The other authors include Caltech postdoc Haixia Huang; grad student Catherine Ward; incoming freshman Jessica Su; biology staff member Lorian Schaeffer; Ming Guo, assistant professor in the departments of neurology and pharmacology at UCLA's Brain Research Institute, David Geffen School of Medicine; and Hay. ☐—*KS*

A rendering of JPL's new "green" Flight Projects Center by its architects, LPA.



So Green, It's Gold

From their campus on the edge of the Arroyo Seco, teams of engineers at the Jet Propulsion Laboratory plan and operate decades-long missions throughout our solar system. Now they've applied this long perspective to their own quarters, beginning with the groundbreaking May 7 of a six-story "green" building whose efficiencies will benefit JPL and its environment for decades to come.

The new Flight Projects Center will reduce its environmental footprint in ways both low- and high-tech: from bike racks and showers for bicycle commuters to "smart ventilation" that regulates airflow according to usage as measured by CO_2 sensors that determine the number of people in a room.

NASA requires that all new buildings be silver-level certified under the Leadership in Energy and Environmental Design (LEED) rating system, established by the nonprofit U.S. Green Building Council. The rating system encourages the design and construction of buildings that are better for both their occupants and the environment. Says Mark Gutheinz, JPL's manager of facilities engineering and construction, "I wanted to see if we could push the designers. This will be the first gold-certified building in the NASA inventory."

The designers managed to go gold while remaining within the building's $65 million budget, and its demand-reducing features will earn JPL a total of about $100,000 in up-front rebates from both Southern California Edison and Pasadena Water & Power. And then there's the long-term reduction in utility bills for the lifetime of the building.

The new building will also save JPL money in other ways. "Projects turn over on a regular basis, so we have to keep creating space," Gutheinz says. "We spend a lot of money here moving people around." The Flight Projects Center is designed to accommodate each project group during the project's early phases, when specialists from all over JPL need a common work space. Different groups will cycle through, but the modular work spaces won't need to be reconfigured.

Less tangible but equally important will be the comfort and morale of the 625 people who will begin to inhabit the building in 2009. The building's gold certification also recognizes the quality of its indoor environment, giving points for attention to details like thermal comfort and construction from low-vapor-emitting materials.

Expanses of windows on the upper floors will offer views of the first-floor auditorium's green roof, landscaped with native, drought-resistant plants. "What's going to be noticed most immediately is the amount of daylight," Gutheinz says. "You're going to feel like you're outside no matter where you are in the building." But all that greenery isn't intended merely to refresh the soul—the plantings help keep the building warm in the winter and cool in the summer, and help filter air pollution all year round. ☐—*JA*

Speaking of green things and outer space, the grass may not always be more verdant on the other side of the star cluster. So concludes a study at Caltech's Virtual Planetary Laboratory that was recently published as two papers in *Astrobiology*. Depending on the range of colors emitted by the local sun, leaves in other hues might be the most efficient at soaking up the available energy. This illustration, by *E&S*'s own Doug Cummings, was published in the July 2007 issue of *Discover*.

A Rubber-Band Laser

Even if you never find one in your Cracker Jack box, the 10-cent tunable dye laser opens up a world of possibilities. A Caltech collaboration between Demetri Psaltis, the Myers Professor of Electrical Engineering, and Axel Scherer, the Neches Professor of Electrical Engineering, Applied Physics, and Physics, has produced a microfluidic "chip" that contains such a laser, a feat that could make a variety of laboratory-grade diagnostic tests as readily available as disposable plastic thermometers.

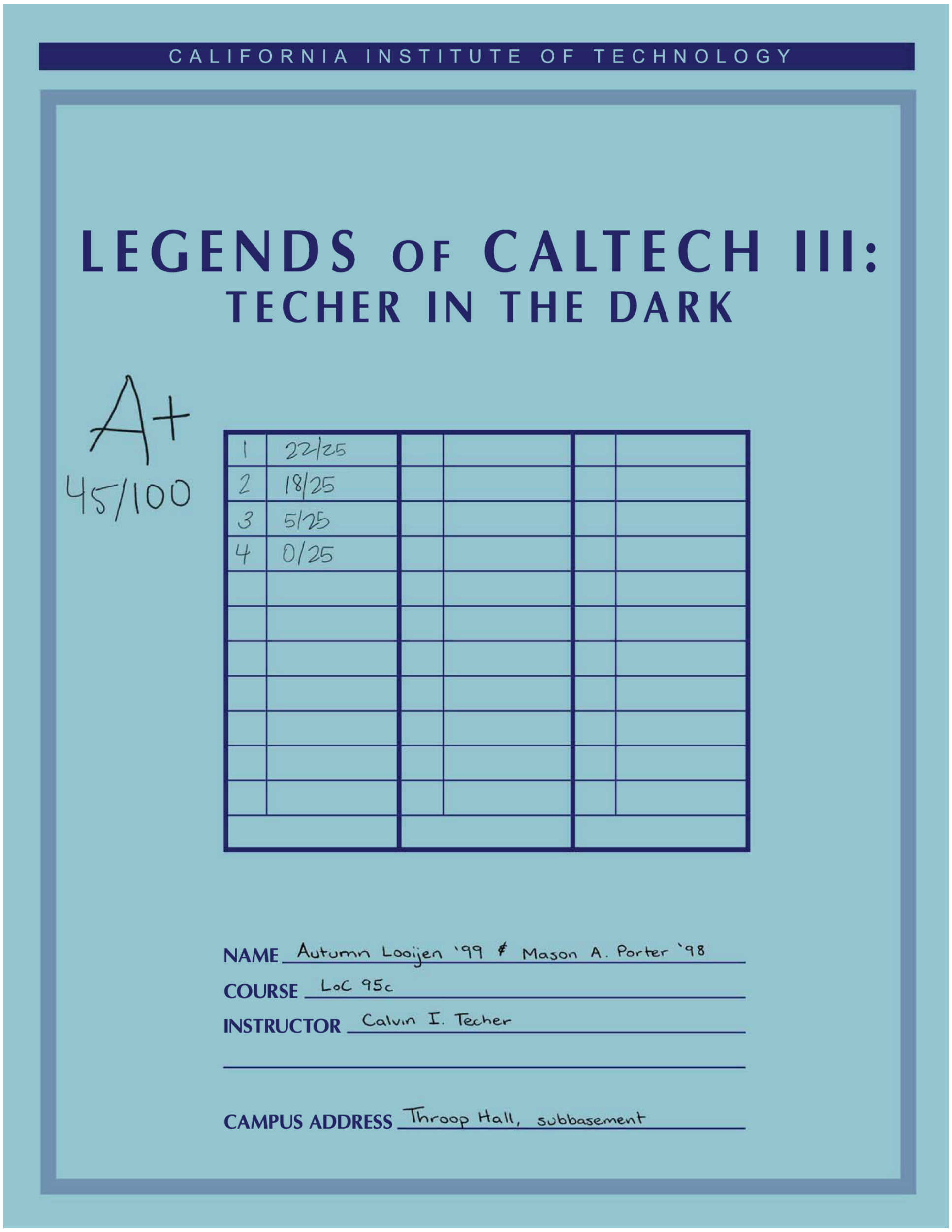
Microfluidic devices can send very small samples through multiple simultaneous analyses, and putting a laser on the chip adds spectroscopy to the toolbox. Inexpensive, single-use devices preloaded with the necessary chemicals would be perfect for biomedical applications. "You take your spectrum and then throw it away," Scherer says. A paper on the work, by grad students Zhenyu Li and Zhaoyu Zhang (MS '06), Scherer, and Psaltis, will appear soon.

The group uses a process called replication molding to stamp out any number of copies from a single, precisely machined master, similar to the way the music industry made vinyl recordings available to millions. "You could do this in your garage," Scherer says. "I *have* done this in my garage."

These records are pressed in silicone rubber—clear, flexible, and very cheap. "This is bathroom caulk," Scherer says. Inject dye into the device with a syringe, and with a boost from an external light source, your laser is ready to go. The group used the equivalent of a green laser pointer to pump the dye, but portable devices could use built-in chemical or semiconductor light sources. Yet don't let the simple means and humble materials fool you. "This does the same job as a $20,000 tunable dye laser."

In some ways it may even do more. All lasers emit a mix of colors, and with dye lasers that mix can be very broad. That's what makes them tunable—if you can pick out just the narrow range of colors you want. This penny-sized device uses a series of evenly spaced pillars, running in a line down the center of the laser cavity's fluid channel, to act as a diffraction grating. The laser is excited by an external source, and the grating allows only the light whose wavelength matches the pillars' spacing to be emitted.

Yet rubber is flexible. Squeeze or stretch the device with your fingers and the spacing changes, as does the laser's wavelength. Try that with your $20,000 instrument! ☐—*JA*



The third volume chronicling Caltech pranks is out. Edited by Autumn Looijen (BS '99) and Mason A. Porter (BS '98) and published by the Caltech Alumni Association, *Legends III* picks up where *Legends of Caltech* and *More Legends of Caltech* left off, and also successfully captures some lesser-known tales of Caltech pranking dating back to the 1950s. Stunts in this instalment include reengineering a building elevator to consistently deliver passengers two floors below where they wanted to go; converting Hell Alley, the hottest hallway in Blacker House, into an ice rink in homage to a resident who was going to get married "when Hell freezes over;" and mating one of the original Compaq PCs to a Lloyd House Coke machine in the days before e-commerce so that purchases could be debited to a student's account. (For a while, those of legal age were even able to buy beer from the machine.) So what's next? *Legends IV*, of course—a website (http://www.legendsofcaltech.com) includes a form on which your own stories may be submitted, as well as additional stories that didn't make it into print.

Legends III , whose cover art depicts the dreaded "Blue Book" used for Caltech finals, is available at the Caltech Bookstore for $12.95. It can also be ordered online at http://www.bookstore.caltech.edu/. A dollar from the sale of each copy goes to the Caltech prank fund. □—*DW-H*

Plastic Food?

In 1967, the career advice given to a certain graduate played by Dustin Hoffman was "plastics." Forty years later, Caltech chemical engineering professor Julia Kornfield (BS '83, MS '84) would add "shish kebabs."

Shish kebabs are beautiful, tiny structures that can form when polymers crystallize during flow. When magnified a million times, they resemble a skewer running through a stack of bell peppers. Inside plastics, they make car body panels stiff and carpet fibers strong, and impart a nice, glossy finish. But they're not without their problems—they might help you to resist a scratch, but they might also cause a layer to peel off. And that's why people want to control them.

Kornfield, Yoshinobu Nozue at Sumitomo Chemical Company, and coworkers have upended the conventional wisdom about how shish kebabs form. Shish kebabs occur in polymers known as polyolefins, which make up half of all plastics used—over 100 million tons per year. In addition to being used for car parts, polyolefins are also used to make pipes, wire, cable, carpets, fabrics, disposable syringes, and many other things. Manufacturers can custom-design a polyolefin's properties by varying its degree of crystallinity and the way the crystals come together. The result can be as hard as steel or as soft as a rubber band.

PICTURE CREDITS: 2 — Bob Paz; 5, 6 — Caltech Archives; 6-7 — NASA, NASA/JPL/U. of Arizona; 9 — Doug Cummings

"The plastics industry can tailor-make molecular distributions, but we don't know how to manipulate them," Kornfield explains. "This discovery opens up a whole new neck of the woods that people didn't know they could explore, and they'll be able to create combinations of properties you couldn't get before."

Much as an inspiring leader can influence the action of thousands, the researchers discovered that some molecules—especially the long ones—can marshal many others to create the shish, which then direct the formation of kebabs. This knowledge will allow for greater control of the creation process itself.

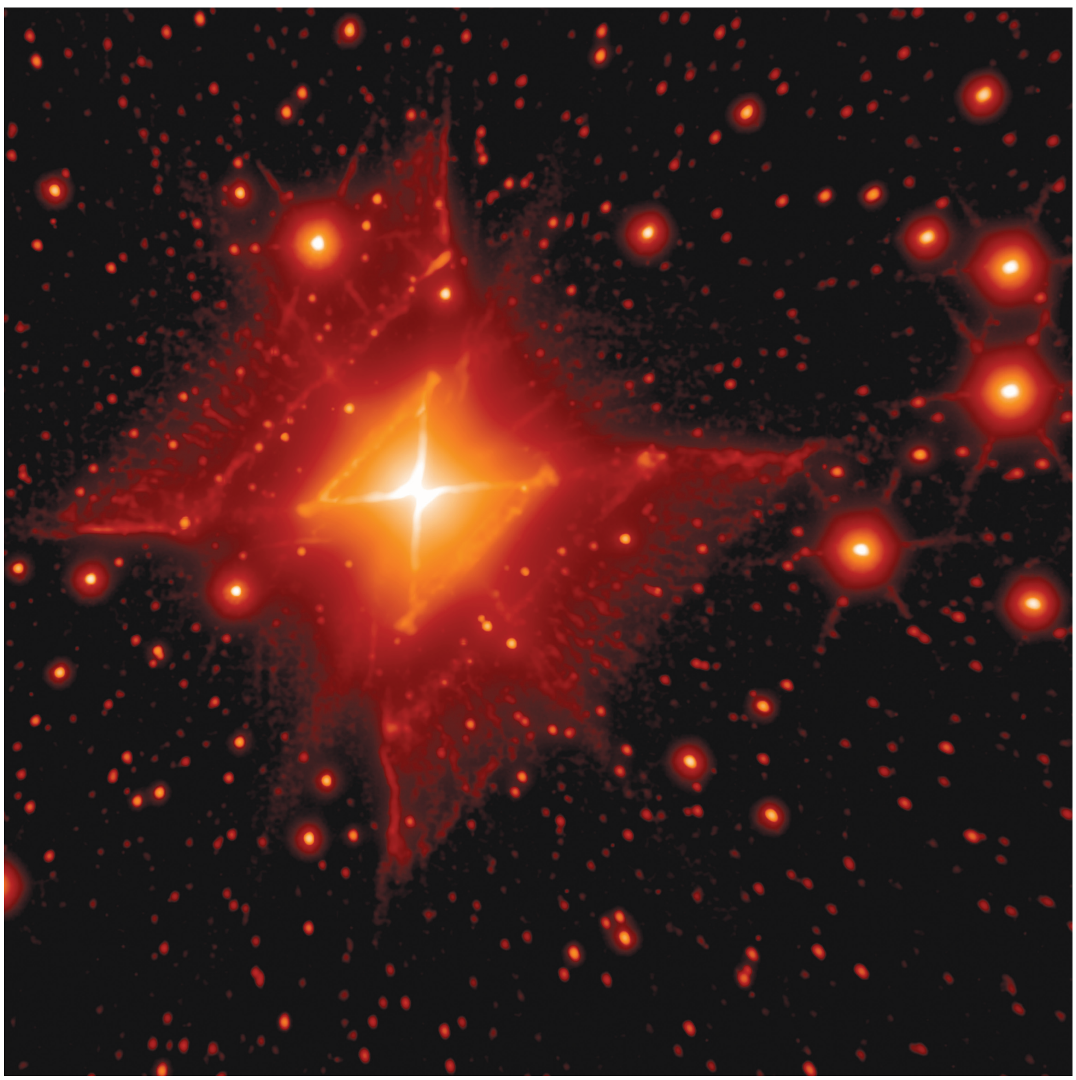
"In other words," says Kornfield, "you could make things by injection molding that you couldn't make before, and injection molding is a very cheap, fast process—you can pop a plastic bumper for an automobile out of its mold in a couple of minutes. So you bring down the cost of manufacturing and at the same increase the throughput."

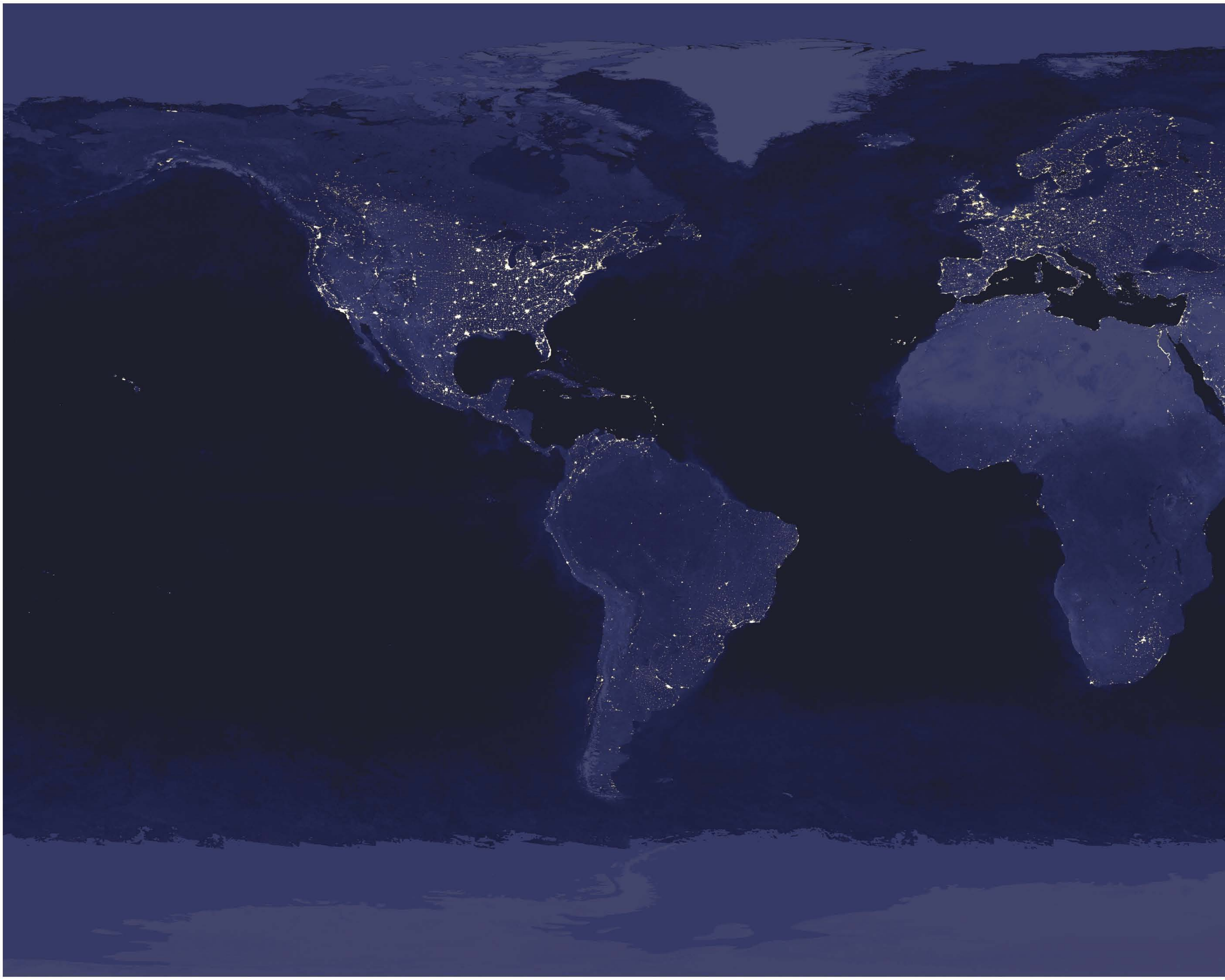
A paper describing the work appeared in the May 18 issue of *Science*. The lead author is Shuichi Kimata, a former postdoc in Kornfield's lab, who played a central role in linking Kornfield's group at Caltech with Yoshinobu Nozue's group at Sumitomo and collaborators at the University of Tokyo. ☐—*RT*

The 200-inch Hale Telescope at Caltech's Palomar Observatory, fitted with an adaptive-optics system that removes atmospheric blurring, has found a star unlike any ever seen before. Those lines that form a near-perfect square aren't some sort of camera artifact—they're real clouds of gas in two hollow cones whose mutual vertex is a hot star called MWC 922 in the constellation Serpens, the serpent.

Christened the "Red Square" by Peter Tuthill of the University of Sydney, leader of the imaging team, the finding was published in the April 13 issue of *Science* in an article coauthored by James Lloyd of Cornell, which provided the infrared camera. The lines pointing out from the center that look like teeth of a comb may be "shadows cast by periodic ripples on the surface of an inner disk close to the star," said Lloyd.

This image, which is not in the paper, was taken in near-infrared light at 1.6 microns. It incorporates data from the Keck II telescope as well as the Hale, and has been sharpened to enhance faint details.





From NASA's Visible Earth website, http://visibleearth.nasa.gov. Data courtesy of Marc Imhoff, NASA/GSFC, and Christopher Elvidge, NOAA/NGDC. Image by Craig Mayhew and Robert Simmon, NASA/GSFC.

Powering the Planet

By Nathan S. Lewis

This talk was the opening keynote speech at the first annual California Clean Innovation Conference, held at Caltech on May 11, 2007. The event, a partnership with UCLA and UC San Diego, included discussions on the futures of assorted energy technologies and how to finance them. In other sessions, clean-energy startup companies were given the opportunity to "fast pitch" their business plans, in three to five minutes each, to a panel of venture capitalists.

Nathan S. Lewis (BS '77, MS '77) is Caltech's Argyros Professor and professor of chemistry. Much more on global energy issues and on his own research in solar power can be found at http://nsl.caltech.edu.

This article was edited by Douglas L. Smith.

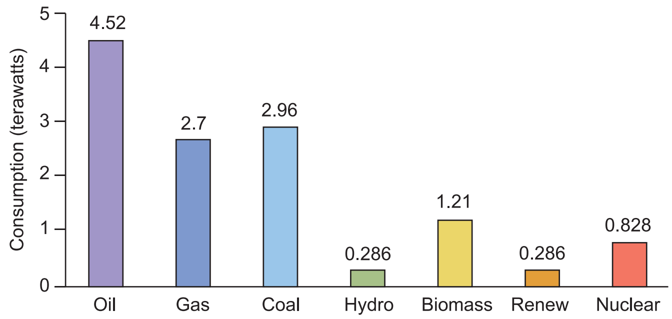
The Scale of Energy

Energy is *the* single most important technological challenge facing humanity today. Nothing else in science or technology comes close in comparison. If we don't invent the next nano-widget, if we don't cure cancer in 20 years, like it or not the world will stay the same. But with energy, we are in the middle of doing the biggest experiment that humans will have ever done, and we get to do that experiment exactly once. And there is no tomorrow, because in 20 years that experiment will be cast in stone. If we don't get this right, we can say as students of physics and chemistry that we know that the world will, on a timescale comparable to modern human history, never be the same.

The currency of the world is not the dollar, it's the joule. Consider the image at left, for example. (I always have to explain to a lot of audiences, although I'm sure not this one, that this picture wasn't taken all at once.) You can see exactly where

Earth's city lights as seen from space. The brightest areas are not necessarily the most populous—compare China and India to the U.S. and Western Europe.

The world's energy diet is about four-fifths fossil fuels. "Biomass" means unsustainable burning of plant material; that is, burning it faster than it can be grown back. "Hydro" stands for hydroelectric power; "renew" means renewables—chiefly sustainable burning of biomass, but this category also includes solar, wind, and geothermal.



the consumption of electricity is. You can also see that there's an inordinate number of people who only have one candle to burn at night. They can't get out of poverty, they can't cure disease, they can't boil water, they can't do much of anything without energy. And they certainly can't save much energy.

Humanity's current energy consumption rate is 13 trillion thermal watts, or 13 terawatts. (My energy data all comes from peer-reviewed sources, primarily the World Energy Assessment report published by the United Nations Development Program, the latest version of which is available online at www.undp.org/energy/weaover2004.htm.) If you took the heat content of all the energy we consume in whatever form—kilowatt-hours of electricity, barrels of oil, cubic feet of natural gas—in a year, and divide it by the number of seconds in a year, you get thermal watts, which I will use as my standard unit, for ease of comparison. And, to refresh your memory, a watt is a joule per second. Politicians talk about changing a few light bulbs in Fresno to compact fluorescents. That's nothing compared to the 13 terawatts that the whole globe consumes, on average. This is the scale of energy.

The Stone Age did not end because we ran out of stones, and the fossil-energy age is not going to end any time soon because we've run out of cheap fossil energy. *Don't wait for that to happen.*

The United States consumes a quarter of the world's energy, at a rate of about 3.3 terawatts, but I won't say anything more about the United States. To physicists, it's not important. I care more about the 13 terawatts. Of the global consumption, about 85 percent comes from fossil fuel—coal, natural gas, and oil. These are primary fuels, that is, direct energy sources. And about 4.5 terawatts of that is used to make electricity—a form of secondary energy—resulting in the generation of about 1.5 terawatts of electricity.

I need to dissuade you up front from one important notion, that some low-cost process is magically going to take us away from fossil energy within the next 20 or 30 years. That's simply false. The Stone Age did not end because we ran out of stones, and the fossil-energy age is not going to end any time soon because we've run out of cheap fossil energy. *Don't wait for that to happen.* Any new energy-creating process is going to be a substitution product. It's not like the cell phone that's ringing in this audience as I speak, where people will pay a lot of money for the privilege of being the first person on the block to be able to annoy everyone else. Whether electricity comes from clean or green or mean does not matter to the end user. They only care that it comes out for a nickel a kilowatt, or less, because that's what electricity from coal and natural gas costs.

Selling a substitution product requires fostering a marketplace where the technology can come to scale and compete. You can't wait for the cost of a mature, competing technology that is already at scale to rise fast enough, soon enough, to make the new technology affordable. There is no way to compete with technology that consists of just taking concentrated energy sources, like coal and oil, pulling them out of the ground, and burning them. We can discuss the true costs of putting carbon into the atmosphere, but on the current economic basis, if we wait for price signals to drive us away from fossil energy, we'll be waiting a very long time.

Dividing our proven reserves by 1998 consumption rates shows that we have 40 years' worth of proven reserves of oil. This is what's in the ground that we can actually book with 90 percent confidence. People look at this and say, "We're going to run out of oil in 40 years!" That's wrong. The ratio of proven reserves to consumption rates has been that same 40 years since the day after oil was discovered. If it costs a million dollars a day to drill a well, and three out of four wells turn up dry, it's not a good use of a corporation's capital to prove out more than 40 years of reserves. So you do that, and then you do something else with the money, like return it to your stockholders. On a net-present-value basis, it doesn't pay to prove out 100 years worth of reserves, so you *always* have about 40 years worth of proven reserves.

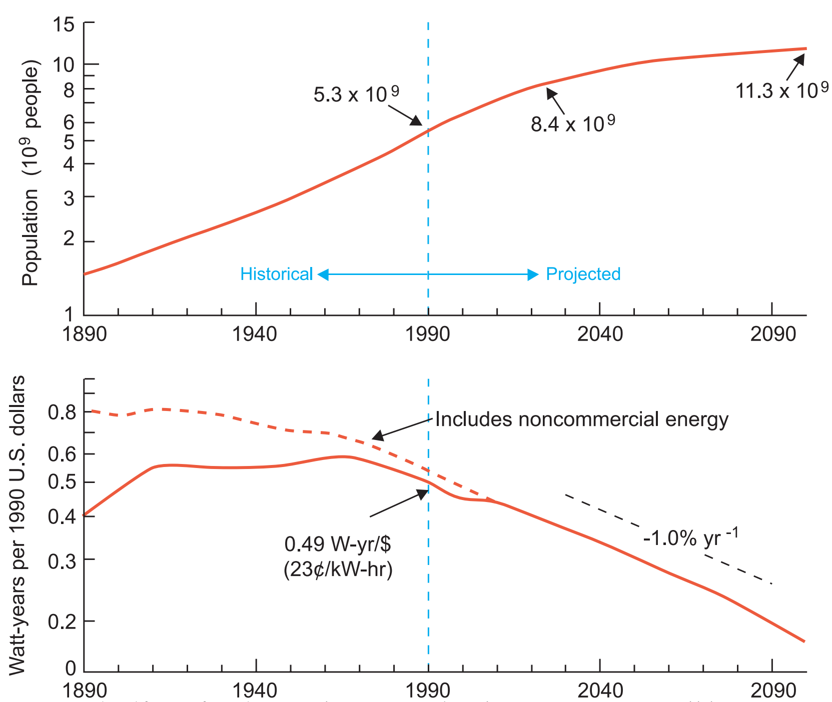
It's certainly true that most of the cheapest oil has been discovered, we believe. On the other hand, $30 a barrel was thought to be prohibitively expensive three years ago, when the U.S. Energy Information Agency was forecasting $24-a-barrel oil through 2025. Crude oil futures are now in the $60-per-barrel range. And the higher the price goes, the more reserves you can access economically. The entire resource base—the best estimate of what's waiting to be discovered—gives us between 50 and 150 years at 1998 consumption rates. And if we should run out of oil, we have between 200 and 600 years of natural gas, and something like 2,000 years of coal. We know how to convert coal into oil—the Germans did it during World War II, and South Africa does it right now. In the United States, we could liquefy coal for $40 a barrel, but investors don't even want to do that because they're not sure that even at that price it would be profitable in the long term.

In the Year 2050

"It's hard to make predictions, especially about the future." But that's never stopped us anyway. The graphs I'm about to show you come from a paper that Martin Hoffert, a physicist at New York University, and colleagues published in *Nature* in 1998, which in turn draws on data from the 1992 United Nations Intergovernmental Panel on Climate Change, or IPCC, report 15 years ago. The IPCC report was recently updated, but the findings remain essentially the same. So this is not new news.

I'm going to focus on the year 2050, which is not 43 years from now, it's five to 10 years from now. Our energy infrastructure has a capital-investment sunk cost that lasts for 40 years, so when you think about 2050, you think about that *now*. In addition, most of us—either our kids or ourselves—are going to be alive in 2050, so it's a good year to look at.

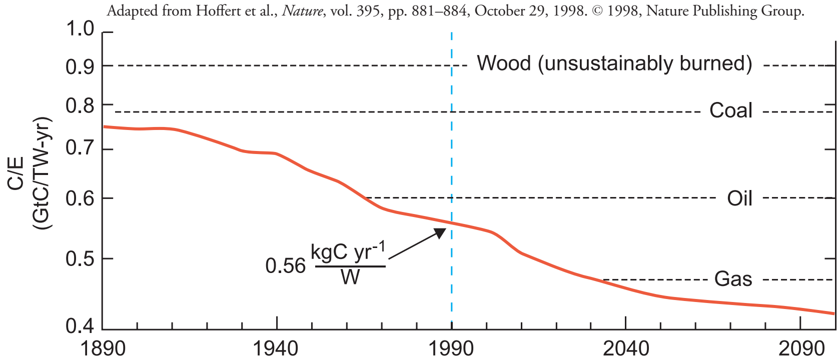
Obviously, people use energy. The world population is projected to be nine to 10 billion people by 2050 (we're at about six billion now), so I'll pick 10 as a round number. And I'll assume a gross domestic product, or GDP, growth of 1.6 percent per year per capita, which the IPCC calls the "business as usual" scenario, based on the average global GDP growth over the last century. The IPCC did not foresee, 15 years ago, 10 percent growth annually in China, and 7 to 10 percent in India. And the developed countries now believe that 4 to 5 percent growth is sustainable. But this doesn't matter, as the numbers just get worse as it gets higher. And



Adapted from Hoffert et al., *Nature*, vol. 395, pp. 881–884, October 29, 1998. © 1998, Nature Publishing Group.

Top: This global population projection, taken from historical data and the Intergovernmental Climate Change Panel's "business as usual" scenario, hits 11 billion people by 2090 and keeps climbing—don't be fooled by the logarithmic vertical axis.
Bottom: The ratio of annual energy consumption per captia to gross domestic product per capita has been falling off in recent years as technology gets more efficient. The "business as usual" scenario assumes this will continue.

Adapted from Hoffert et al., *Nature*, vol. 395, pp. 881–884, October 29, 1998. © 1998, Nature Publishing Group.



The IPCC's "business as usual" projection tracks how the carbon-to-energy ratio of our global energy mix has declined over time. But this trend cannot continue below the carbon-to-energy ratio of the cleanest carbon component without a substantial influx of carbon-free power. "GtC/TW-yr" stands for gigatons of carbon per terawatt-years.

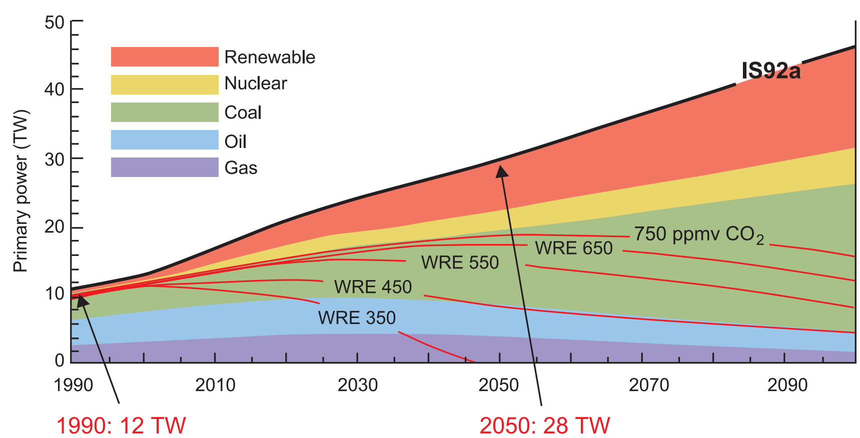
no country that I'm aware of has a policy *against* economic growth.

With population and GDP growth conspiring together, we would then obtain a tripling of energy demand by 2050. This is partly mitigated, however, by the fact that we're using energy more efficiently per unit of GDP. The ratio of energy consumption to GDP has been declining at about 1 percent, globally averaged, per year. The United States actually saves energy at a faster rate, about 2 percent per year. Because we have such a high per-capita energy baseline consumption, it is easier for us to save off that base, whereas the developing countries save less. The "business as usual" scenario assumes that this will continue, and if we project that down, we will achieve an average energy consumption of two kilowatts per person within our lifetimes. (The United States now uses 10 kilowatts per person.) But factor in population growth and conservative economic growth, and we'll still need twice as much energy as we need now.

In terms of average thermal load, a person on a 2,000-calorie-per-day diet is basically a hundred-watt lightbulb. And in our highly mechanized western agricultural system, the energy embedded in food—to run the farm and grow the food and transport it to the supermarket and put it in the refrigerator—is 10 to 20 times the energy content of the food itself. And the farther you live from the food source, the more embedded energy you consume. If we are 100-watt lightbulbs, this means that just keeping us fed requires one to two kilowatts.

The other thing we need to consider is the amount of carbon emitted per unit of energy produced, or the so-called carbon intensity of our energy mix on average. Back in the Stone Age, the carbon-to-energy, or C/E, ratio was quite high, as we were burning wood in caves. That's very inefficient. Most of the energy escapes into the air. We then moved to coal, and coal is not bad engineering, it's bad chemistry. We know how to burn coal efficiently, and when we burn all the carbon we get all carbon dioxide. When we burn natural gas, that's CH_4, we get one molecule of CO_2 but two H_2Os. So relatively more of the heat content in joules is delivered by making H_2O rather than forming CO_2. Natural gas is thus more energy-efficient on a carbon-emitted basis. And oil is in between, having a chemical formula of CH_2, on average. These figures are constants you can do nothing about. They are simply the products of the chemical formulas and the heats of combustion of coal, oil, and natural gas.

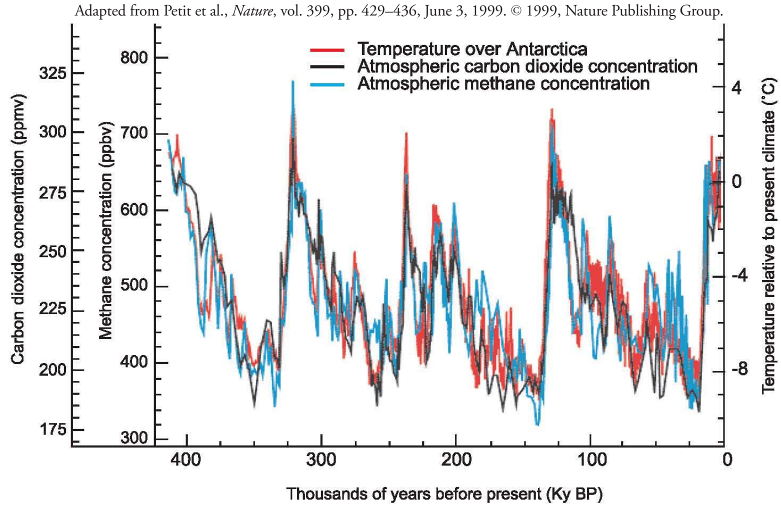
If we follow the "business as usual" C/E projection, which is hardly business as usual except for drawing straight lines into the future, it predicts by 2050 an average carbon intensity of 0.45, which is lower than that of the least-carbon-intensive fossil fuel, natural gas. And the only way you can do that is with a significant infusion of carbon-free or carbon-neutral power, to bring the overall average lower than the least of its carbon-based components. Furthermore, if you accept that we continue to burn oil and coal, because they are cheap, we'll need even more carbon-neutral energy to bring us



The heavy black line shows humanity's primary-power consumption in the "business-as-usual" scenario. The red lines show the carbon-based power consumption reductions needed to stabilize atmospheric CO_2 at various levels.

Adapted from Hoffert et al., *Nature*, vol. 395, pp. 881–884, October 29, 1998. © 1998, Nature Publishing Group.

Adapted from Petit et al., *Nature*, vol. 399, pp. 429–436, June 3, 1999. © 1999, Nature Publishing Group.

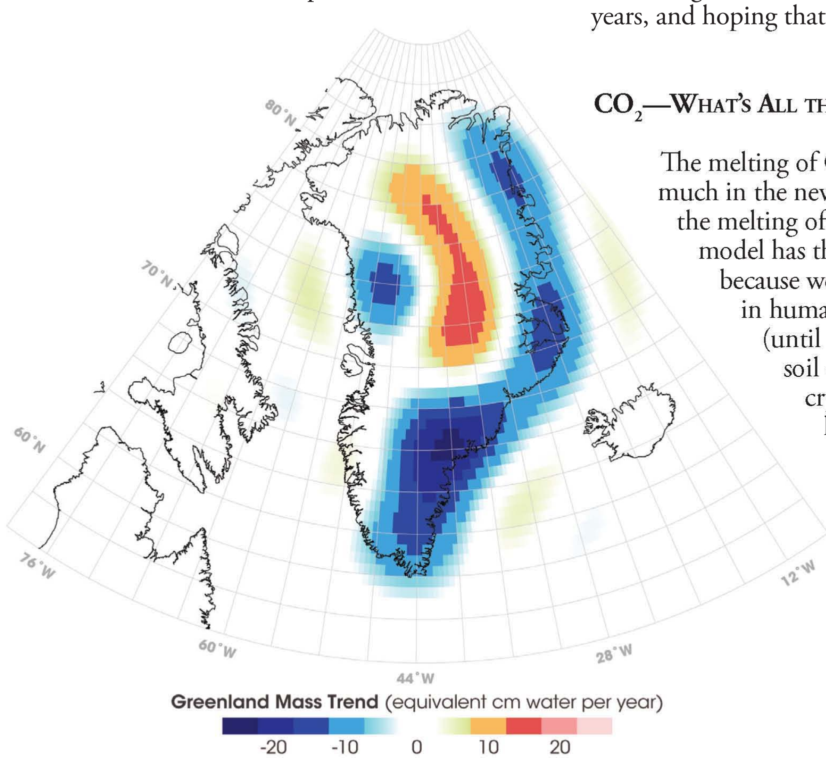


The last 425,000 years' worth of data from ice cores drilled at Vostok, Antarctica, show that the levels of atmospheric carbon dioxide and methane, both greenhouse gases, go hand in hand with average temperatures.

down there. But I'll assume we will do that, too.

So we've magically, somehow, added enough carbon-free power that we can stay on this decarbonization curve. And I'll further assume that we've implemented highly aggressive energy efficiency to reduce our total demand per person down to two kilowatts. This assumes that we can get the energy embedded in our food down to one kilowatt as part of that aggressive conservation program, and that leaves us with one kilowatt per person to heat our houses, get to work, play video games, and do everything else we do. And under those assumptions, if we relate the amount of carbon emitted to the amount of energy consumed, it is simple arithmetic to calculate the amount of carbon that we will release into our atmosphere. That set of calculations brings us to the heavy black line labeled IS92a, which is the IPCC's shorthand name for this particular "business as usual" scenario.

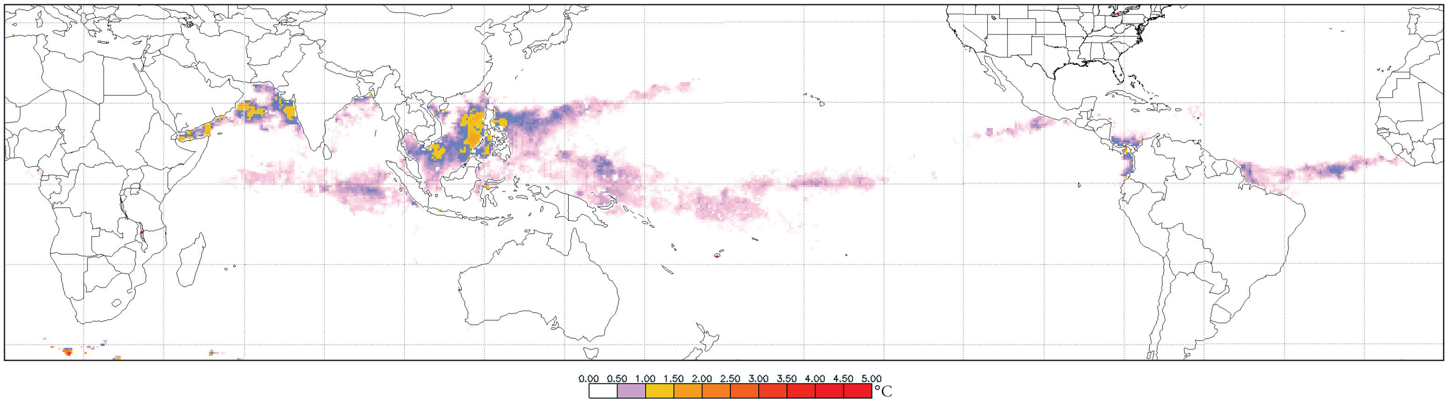
However, this is *still* insufficient to stabilize the atmospheric levels of CO_2 at any reasonably acceptable levels. Ice cores taken near Vostok Station, Antarctica, show that the CO_2 level has been in a narrow band between 200 and 300 parts per million by volume (ppmv) for the last 425,000 years; data from other cores have extended this back to 670,000 years. Current CO_2 levels are about 380 ppmv. "Business as usual" will require 10 trillion watts, 10 terawatts, of carbon-free power, and it never stabilizes CO_2 levels—they just keep going up. So even on that track, we are betting against data that goes back for almost a million straight years, and hoping that this time, we get lucky.



Observations made by NASA's Gravity Recovery and Climate Experiment (GRACE) satellites show that between 2003 and 2005, Greenland's low coastal areas shed 155 gigatons (183 cubic kilometers) of ice per year, while snow accumulation in the interior was only 54 gigatons per year. This two-year ice loss is roughly equivalent to the amount of water that flows through the Colorado River in 12 years.

CO_2—What's All the Fuss About?

The melting of Greenland's ice pack has been much in the news, but let's talk instead about the melting of the permafrost. No climate model has that nonlinear effect built in, because we have no experience of it in human history. Permafrost is the (until now) permanently frozen soil of the tundra, and as the ice crystals in it melt, it reflects less light and turns darker, absorbing more light, and that melts more permafrost. Helium dating of trapped bubbles in the permafrost shows that we're melting permafrost now that hasn't been melted in 40,000 years. And there's enough CO_2 and methane (another



http://www.osdpd.noaa.gov

Oceanic hot spots on June 11, 2007, as compiled by the National Oceanic and Atmospheric Administration's satellites. A hot spot is defined as a region where the sea-surface temperature is at least one degree Centigrade greater than the maximum expected summer temperature. These warmer waters can lead to the bleaching and eventual death of coral reefs.

greenhouse gas) trapped in the permafrost to have the greenhouse gas levels not go up by a factor of two but by a factor of *10*.

The world was there at least once before, most recently in the Permian era 250 million years ago. There was a massive release of isotopically light carbon from unknown causes, and CO_2 levels rose by a factor of 10. (The fast release rate and the isotope ratio suggest it was some sort of self-catalyzing event, such as permafrost melting, as opposed to, say, a volcanic release.) Temperatures spiked for on the order of tens of thousands of years, and the fossil record shows that about 90 percent of the species on the planet went extinct. We do not know if this will happen again. We do know that there is only one way to find out.

The CO_2 we produce over the next 40 years, and its associated effects, will last for a timescale comparable to modern human history. This is why, within the next 20 years, we either solve this problem or the world will never be the same. How different that world will be, we won't know until we get there.

We also know that, unfortunately, there is no natural destruction mechanism for carbon dioxide in our atmosphere. Unlike ozone depletion, it will not heal by itself through chemical processes. In our highly oxidizing atmosphere, CO_2 is an end product. The lifetimes of CO_2 in the atmosphere are well known, and the time for 500 to 600 ppmv of CO_2 to decay back to 300 ppmv is between 500 and 5,000 years. Which means that the CO_2 we produce over the next 40 years, and its associated effects, will last for a timescale comparable to modern human history. This is why, within the next 20 years, we either solve this problem or the world will never be the same. How different that world will be, we won't know until we get there.

Although major uncertainties remain, most climate-change researchers set 550 ppmv as the upper limit of what would lead to about a two-degree-Centigrade mean global temperature rise. This is projected to have significant, but possibly not catastrophic, impacts on the earth's climate. For example, the coral reefs would probably all die. But we, as humans, would probably be able to adapt, at some level, to such a change. On the other hand, most people in the modeling effort feel that 750 ppmv or higher would be quite serious.

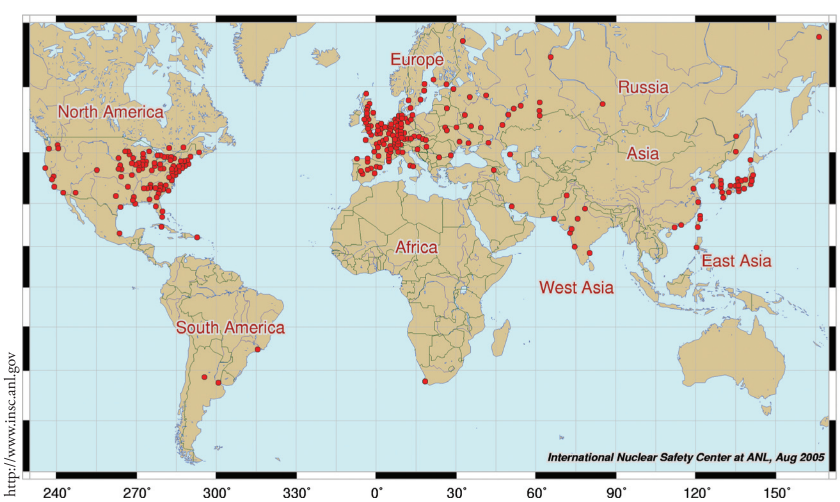
If we want to hold CO_2 even to 550 ppmv, even with aggressive energy efficiency we will need as much clean, carbon-free energy within the next 40 years, online, as the entire oil, natural gas, coal, and nuclear industries today combined—10 to 15 terawatts. This is not changing a few lightbulbs in Fresno, this is building an industry comparable to 50 Exxon Mobils. Furthermore, if we wait 30 years, the amount of carbon-free energy we'll need will be even greater, and needed even faster, because in the meantime we will have put out 30 years of accumulated CO_2 emissions that will not go away for centuries to millennia. So stabilizing at 550 ppmv will then require about 15 to 20 terawatts of carbon-free power in 2050.

These results underscore the pitfalls of "wait and see." Because "wait and see" is "wait and do."

Kicking the Carbon Habit

We absolutely have to have universal, government-based policies to drive this transformation if we are going to make such a transition on this rapid a timescale. As I said, if a substitution product has to compete on a cost basis from Day One with our cheapest energy sources and their economies of scale, we won't get there. "If carbon dioxide is free, we'll take 10." And, contrary to assertions, we simply do not have the technology on the shelf to provide that much carbon-free power cost-effectively today. You will hear people say we have the technology, all we need is the political will. We have the technology to go to the moon, too, but just because we have the political will to give Southwest Airlines a few gates at La Guardia doesn't mean that they'll fly you to the moon and back on a $49 Internet special. It's a question of scale, as well as cost, not solely technology.

Let's talk first about energy efficiency. It's much cheaper to save a joule of energy than it is to make it, because the losses all along the supply chain are such that saving a joule at the end means you save making, say, five joules at the source. So lowering demand with energy-efficient LED lighting, fuel cells, "green" buildings, and so on is going to pay off much sooner than clean energy supplies. On the other hand, if we save as much energy as we currently use, combined, we will still need to make at least as much carbon-neutral energy by 2050 as we currently use, combined, merely to hold CO_2 levels to double where they are now. That's the scale of the challenge.

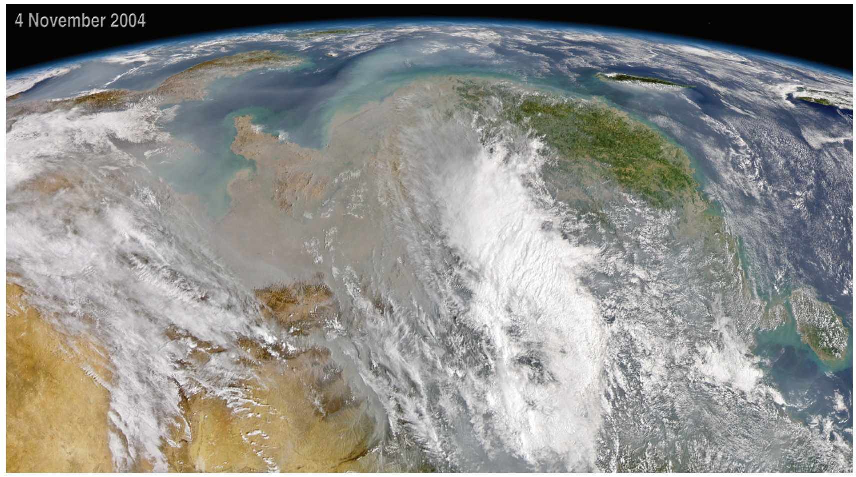


The red dots show nuclear power reactor locations. (Map courtesy of the International Nuclear Safety Center at Argonne National Laboratory.)

So let's look at carbon-neutral energy sources. We could go nuclear, which is the only proven technology that we have that could scale to these numbers. We have about 400 nuclear power plants in the world today. To get the 10 terawatts we need to stay on the "business-as-usual" curve, we'd need 10,000 of our current one-gigawatt reactors, and that means we'd have to build one every other day somewhere in the world for the next 50 straight years. I've been giving this talk in one version or another for five years—we should have already built on the order of 1,000 new reactors, or double what's ever been built, just to stay on track. So we're really behind.

There isn't enough terrestrial uranium on the planet to build them as once-through reactors. We could get enough uranium from seawater, if we processed the equivalent of 3,000 Niagara Falls 24/7 to do the extraction. Which means that the only credible nuclear-energy source today involves plutonium. That's never talked about by the politicians, but it's a fact. Forgive my facetiousness, but on some level we should be thanking North Korea and Iran for doing their part to mitigate global warming. We'd need about 10,000 fast-breeder reactors and, by the way, their commissioned lifetime is only 50 years. That means that after we choose this route, we're building one of them every other day, or more rapidly, forever.

We don't have time for the physicists to figure out how to make nuclear fusion reactors—they've been saying it will be demonstrated (although not economical) in 35 years, and they've been saying that for the last 50. If we assume they're right this time, then ITER, a multinational demonstration fusion reactor being built in the south of France, will demonstrate break even—that is, it will put



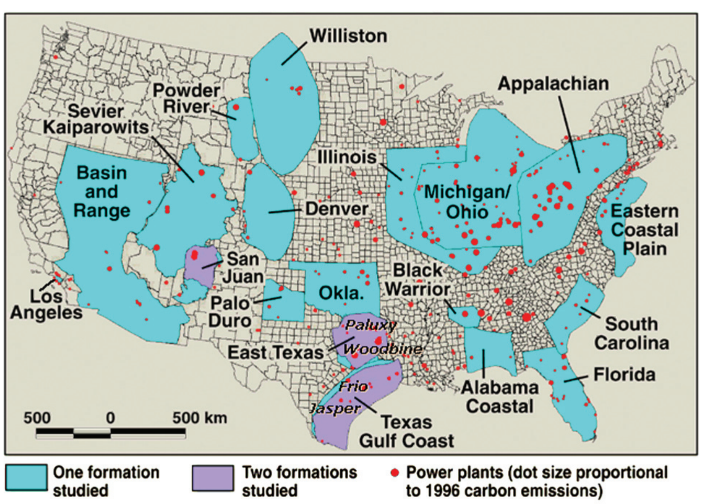
Incomplete burning of coal and wood leads to a buildup of haze in eastern China, where mountains and weather patterns can trap it for days at a time. Here the haze extends from the edge of the Gobi Desert (left) to the South China Sea (right)—a distance of well over 2,000 kilometers. (Image courtesy of the SeaWiFS Project, NASA/Goddard Space Flight Center, and ORBIMAGE.)

out as much energy as it takes to run it—in 35 years, and it will run for all of one week before the entire machine will, by design, disintegrate in the presence of that high-neutron radiation and temperature flux. And in the meantime we would have to build a commercial fission reactor every day for the next 30 years. It's not going to happen.

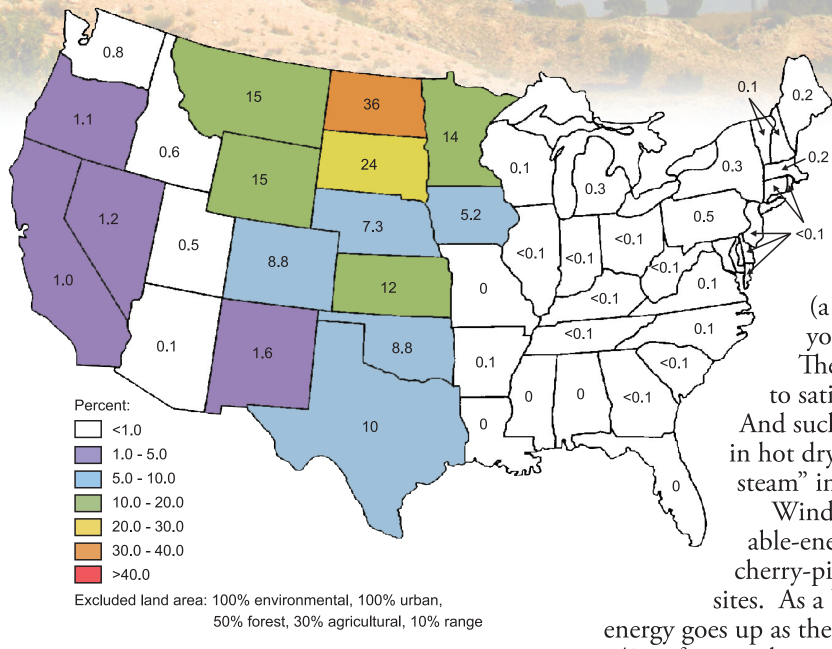
We could get there by sequestering the carbon. We have plenty of cheap coal, globally. China is building two gigawatts' worth of coal-fired electric power plants every week now. We could pipe the CO_2 out to the deep ocean, but CO_2 dissolved in water becomes carbonic acid, and estimates are that in some places the local pH change would be about 0.1 pH units. That's probably not a good idea. We could pump the CO_2 into deep oil and natural gas wells, but there aren't enough of them to hold all the CO_2 we will make during the next 50 years. We could put it in deep aquifers, where there's about 100 to 200 years' worth of total capacity, which would give us enough time to bridge to something else—*if it works technically*. You should not assume that it works yet. The decay time of CO_2 in the atmosphere is, as I said before, between 500 and 5,000 years. That means that if one percent of the CO_2 in the reservoirs leaks, in 100 years the flux to the atmosphere would be identical to what you intended to mitigate in the first place. We know that CO_2 migrates underground. It bubbled up in Lake Nyos, Cameroon, on August 26, 1986, and killed some 1,700 people. So we're going to have to demonstrate within the next 10 years that it will leak less than 0.1 percent, globally averaged, for the next millennium in thousands of different aquifers around the world.

Every site is geologically different. So even if you validate sequestration at one site, that doesn't mean that it will work at the other thousands of sites we'll need. (Of which, by the way, nobody knows whether China has basically any.) And be careful what you wish for, because you might actually get it. *If* it works, a quick calculation based on the density of supercritical CO_2 at 1,000 meters' burial depth indicates that there will be enough buried CO_2 emissions from the United States that within 100 years, if uniformly distributed, it would cause a rise in the elevation of the lower 48 states by about five centimeters. Which will be good if the sea level rises; otherwise not so good.

By the way, I feel that a great way to make money from sequestration is to learn from the past. Think of the American railroads—they didn't make the big money off of hauling goods, they bought up all the land and made money from the towns that the railroads enabled. And so people should go buy up abandoned wells for pennies now, and then rent them for millennia to the utility companies to bury their carbon.



Areas of the continental United States where deep saline aquifers may allow CO_2 sequestration. Many coal-fired power plants are not near such aquifers, which means that CO_2 would have to be piped to them. (Map courtesy of the U.S. Department of Energy.)



The electricity-generating potential of wind from Class 4 and higher sites, i.e., places where the average wind speed at a height of 50 meters above the ground is 28 kilometers per hour or better. The percentage figures compare this potential to 1990 electricity consumption.

Renewable Energy

Which brings us last to renewable resources—biomass, hydroelectric, geothermal, wind, and solar.

Hydroelectric power is a model renewable resource, but all the kinetic energy in all the rivers, lakes, and streams on our planet combined adds up to a rate of 4.6 terawatts. And we can't tap all of that, because we can't dam up the Okeefenokee Swamp and get much energy. So as a practical matter, there's 1.5 or so terawatts available, but that includes places like the Hudson River, and we only want to dam that if the Yankees fire Joe Torre. Similar economic considerations leave us 0.9 terawatts, and we've already built 0.6. So forget about hydroelectricity. It's cheap, it's abundant, and we've pretty much maxed it out.

You'll hear a lot about geothermal energy. The sustainable geothermal heat flux works out to 0.057 watts per square meter. That's from the temperature at the center of the earth, the thermal conductance of the earth, and the diameter of the earth. So from the entire continental surface of our planet, if you captured all of the heat flux at 100 percent efficiency (a small second-law problem!), you might get 11 terawatts. The heat of the earth isn't close to satisfying our thirst for energy. And such deep geothermal wells in hot dry rock tend to "run out of steam" in about five years.

Wind is the cheapest renewable-energy source now, because we cherry-pick the high-wind-velocity sites. As a bonus, the wind's potential energy goes up as the cube of the wind speed—1/2 mv^2 times the mass of air per unit time, which introduces another factor of v. And wind energy is relatively economic, about five cents per kilowatt hour in *very* high-wind-speed areas, but, even adding in the lower-wind-speed areas, when you calculate the total kinetic energy that we can get at the surface of the earth, there is to be had in practical terms about two to four terawatts.

If we assume that the net energy return from biomass equals the gross energy production—that is, that it takes negligible energy input to run the farm and harvest the crop—generating 20 terawatts would require 31 percent of the total land area of the planet—4×10^{13} square meters. The problem is that photosynthesis is fundamentally inefficient. Leaves should be black instead of green. They have the wrong band gap, and they convert less than 1 percent of the total energy they receive from sunlight into stored energy on an annual basis.

And, by the way, the fastest-growing plants known are a mere factor of two or so under their ultimate CO_2 fixation rate. CO_2 is dilute in the atmosphere, so unless there's a transport system sucking carbon dioxide down from above, the natural mass-transport rates limit plant growth to a factor of two or so over the fastest that we already have. So if someone shows you pictures of little

I believe in the Willie Sutton school of energy management. . . . One hundred twenty thousand terawatts of solar energy hits the earth, so Willie Sutton would say go to the sun because that's where the energy is.

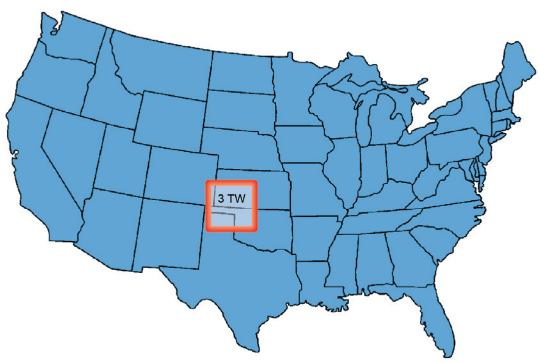
tomatoes and big tomatoes, and extrapolates from tall switchgrass to 20-times-taller switchgrass, that's defying the laws of physics.

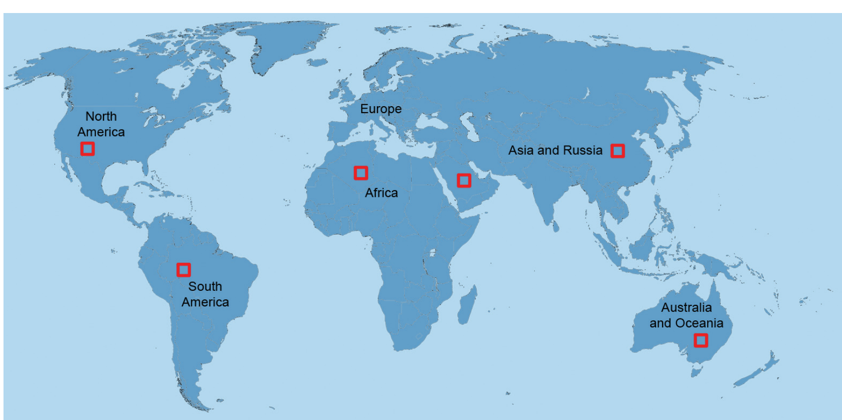
You hear a lot about schools of management. I believe in the Willie Sutton school of energy management. The Willie Sutton principle is simple. Willie Sutton was a famous bank robber, and when they finally caught him someone asked, "Why do you rob banks, Mr. Sutton?" He said, "Because that's where the money is." I believe in that, too.

One hundred twenty thousand terawatts of solar power hits the earth, so Willie Sutton would say go to the sun because that's where the energy is. It is the *only* natural energy resource that can keep up with human consumption. Everything else will run up against the stops, soon. In fact, more solar energy hits the earth in one hour than all the energy the world consumes in a year.

For a 10-percent-efficient photovoltaic system, and the latest systems are 15 percent or better, we could supply all the United States' energy needs with a square of land some 400 kilometers on a side. As you can see in the map at left, this would cover the Texas and Oklahoma panhandles, part of Kansas, and a wee slice of Colorado. The good news is that this area is pretty lightly populated, and the residents of even a few counties there would make enough energy to become full-fledged members of OPEC. And six of these boxes would power the globe. Unfortunately, solar is also far and away the most expensive way we have of making electricity today, with costs ranging from 25 to 50 cents per kilowatt-hour for photovoltaic systems, that is to say solar panels. Solar thermal systems, which I'll talk more about in a moment, run 10 to 15 cents per kilowatt-hour, which is still too expensive. Nobody is going to pay that much for a substitution product, when they can get the original one for four cents a kilowatt-hour.

The only way that we can get this to happen is if we lower the cost of solar converters to something like $10 a square meter. It has to be something you'd buy at Home Depot to paint your roof with. You can't use single-crystal silicon—at this cost, you have to think potato chips, not silicon chips. You have to use really cheap materials, so my lab is trying to make solar cells out of fool's gold and rust.





Top: The nation's entire energy needs could be met by tiling a 400 × 400 kilometer parcel of land in the sunny Midwest with solar panels. Bottom: Six such squares, appropriately sited, could power the world.

Solar thermal systems, in which a parabolic dish of mirrors focuses the sun's energy on a collector, produce cheaper electricity than photovoltaic cells. They can also be easily mated to electrolyzers (the building and cooling towers in the background) to transform that electricity into storable hydrogen fuel. Unfortunately, they don't scale up well.

And we're working on paintable materials based on nanorods of TiO_2, which is the white pigment in paint. The folks at Behr Paint called yesterday to see if we had a bucketful that they could test, and we had to say no. We're still working on it.

And, by the way, if we succeed and make really cheap solar cells, that alone will not solve much in the big picture of energy. Because as Johnny Cochran might have said, "If it does not store / You'll have no power after four." Solar cells convert sunlight into electricity. And there's no good way to bottle up and store vast quantities of electricity. If you have one, go buy electricity off the grid at five cents a kilowatt-hour at night, outside of peak load hours, and then sell it back to the grid at 25 cents per kilowatt-hour in the daytime to balance the load, and laugh all the way to the bank.

I believe that the best way to store massive quantities of electricity is to convert it into chemical fuel. The best technology for that purpose that we have now uses a solar thermal system that collects and concentrates solar energy to electrolyze water. You get H_2 for fuel, which you can distribute through pipelines and store in tanks. And then you can pump it out of the tank whenever you like and run it through a fuel cell, which converts it back into electricity and water. The problem is, the existing technology is not scalable. The setup in the photo above makes about a kilogram of hydrogen—the energy equivalent of about a gallon of gasoline—every day. And we would have to build one of these every second, for 50 straight years, just to hold the CO_2 concentrations to 550 ppmv. We need to find a better way to make fuel from sunlight directly so that we can bring energy to whoever wants it whenever they want it—day or night, summer or winter. My lab and other labs at Caltech are working on that, too.

So, in summary, we're going to need more energy in order to lift people out of poverty and have economic growth. Even if we keep demand flat, it doesn't help us very much because CO_2 emissions are cumulative. And the globe has *never* had a year in which it has used less energy in a year than it did the year before.

No rational energy program would start without promoting energy efficiency. We should do all we can there. But no amount of saving energy ever turned on a lightbulb. No amount of saving energy actually put food on somebody's table. Energy efficiency is simply not enough to bridge the demand gap. On the supply side, there are only three big cards to play, in some combination: coal sequestration, if we dare; nuclear fission involving plutonium, if we double dare; or finding a way to make cheap, storable energy from the other big card that we have, which is the sun. But solar has to be *really* cheap, and scalable, *and* we've got to find a way to store it.

I haven't talked much about economics, but I will say that it's easy to prove, thinking 100 years out, on a risk-adjusted net-present-value basis, that the earth is simply not worth saving. It's a fully depreciated, four-billion-year-old asset. Unless you have policy incentives that reflect the true cost of doing this experiment, the economically efficient thing to do is just what we are doing now. On the other hand, with the appropriate policy incentives, the financial opportunities are commensurate with 50 Exxon Mobils on the supply side, and, in devising ways to lower our energy consumption from triple to double by 2050, 50 more Exxon Mobils on the demand side. This is both the challenge and the opportunity.

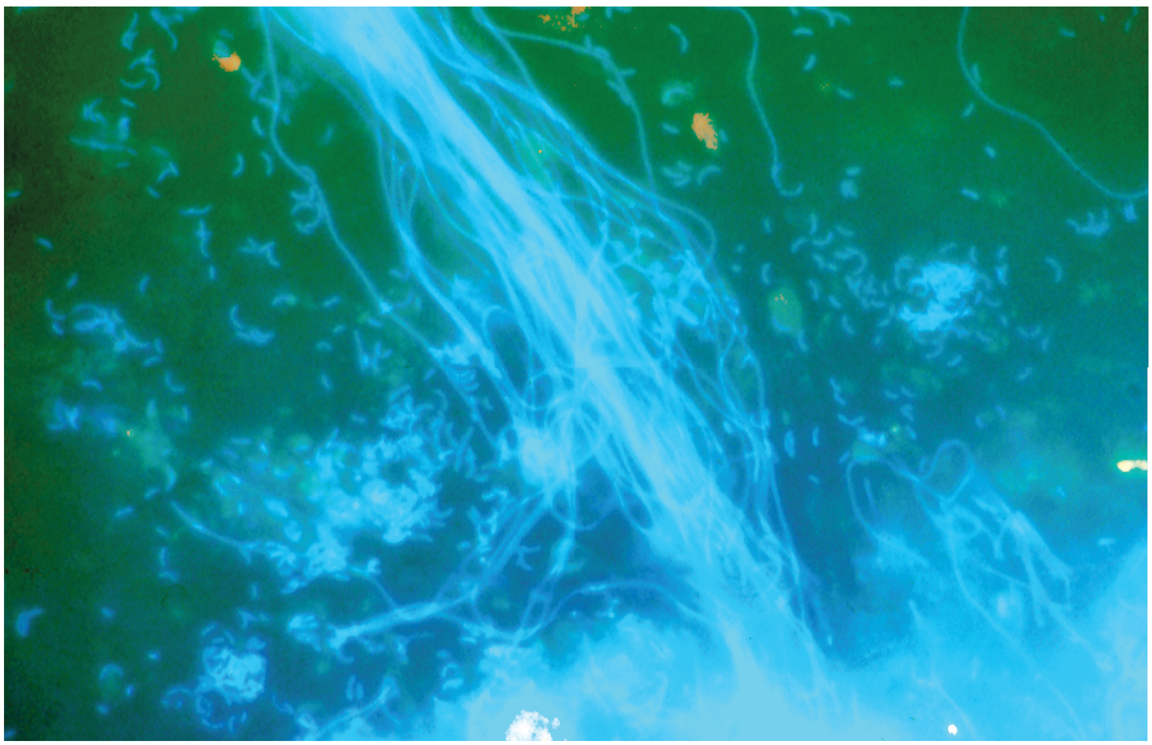
I leave it to you to decide whether this is something that we cannot afford to do, or something at which we simply cannot afford to fail. Remember, we get to do this experiment exactly once. And that time, like it or not, is now. □

PICTURE CREDITS: 14, 21, 22 — Doug Cummings; 17 — NASA

For the Love of Termites

By Elisabeth Nadin

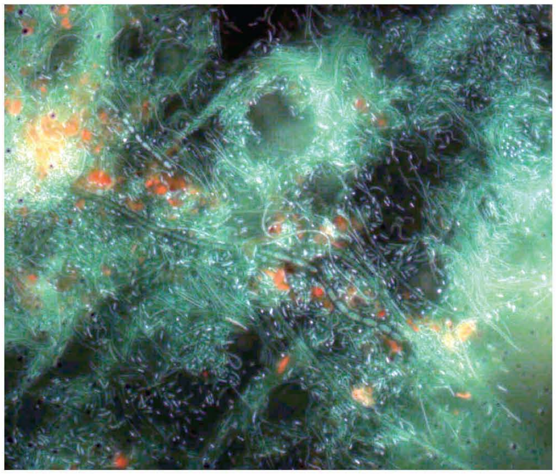
The strange world inside a termite's hindmost gut is inhabited by about 250 different species of microbes. Among them are millions to billions of long, filamentous bacteria and their shorter counterparts—lining the gut's outer skin as shown in this epifluorescence micrograph—which make methane from hydrogen and carbon dioxide.



From Leadbetter and Breznak, *Applied and Environmental Microbiology*, vol. 62, no. 10, pp. 3620–31, 1996.

It's evident by the way he cavalierly handles a slice of wood crawling with centimeter-long, fat, white termites that Caltech associate professor of environmental microbiology Jared Leadbetter has loved insects for a long time. Since he was four years old, in fact—that was when his big sister Briana, then nine years old, brought home mounted butterflies and beetles from her summer entomology course, and he decided that he would study insects when he grew up. But his love affair with termites began only after his junior year in college, during a summer course in microbial diversity at the Marine Biological Laboratory in Woods Hole, Massachusetts. During one lab exercise he found himself staring through a microscope at the insect's spilled guts and, he laughs, "it was basically love at first sight." It was the microbes living inside the gut that particularly fascinated him. "They're exciting to look at; they really catch your eye," he says. "And I thought, 'Aha! This is exactly the right project for me.'" Despite 100 years of investigation, very little was known about the workings of those microbes, further fueling Leadbetter's interest in the single microliter of material housed in a termite's hindmost paunch.

What's in a microliter? For starters, less than what can fill the volume under your pinky fingernail. But in that last of three of a termite's hindguts, a microliter hosts around 250 species of microbes, many of them oxygen-phobic, that digest



This view of the termite's hindgut microbe community turned Leadbetter on to the inner workings of the relationship that keep these symbiotes alive. The termite chews wood, but relies on its gut microbes to turn the particles into an energy form it can use.

Below: A soldier of the *Zootermopsis* genus doesn't gnaw on wood, but uses its pincers to chop off ants' heads.

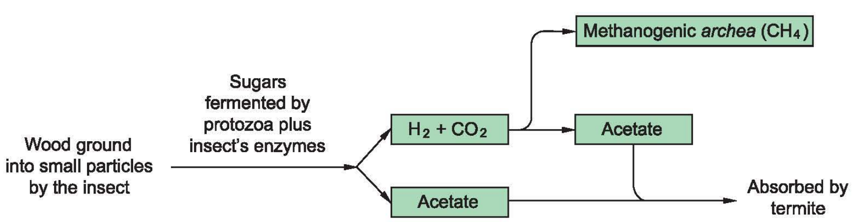
Image © Alex Wild Photography.

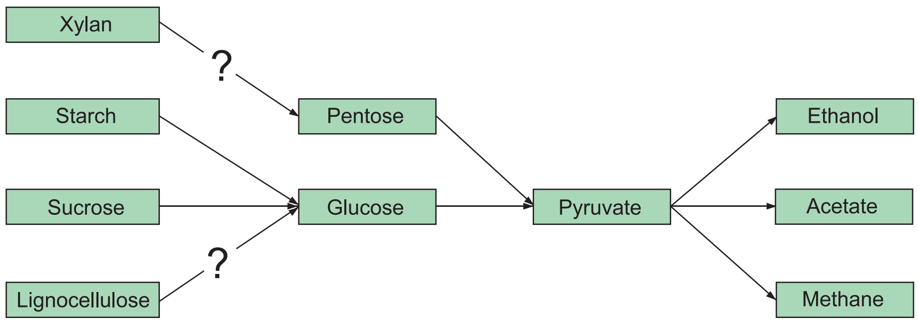
the wood that their host chews. This compensating mutualistic relationship keeps them all alive—termites can't digest their own food, and the microbes can't chew wood or survive outdoors. How the relationship evolved into the near-perfect symbiosis it is today is still an intriguing mystery. "It's one thing to consider how precarious any single life is, whether it's a microbe or an insect or a human. Then to have this interrelationship between two hundred different members—it seems doomed to failure. They're not even the same species, and they all have their individual needs, but they also have a shared need. To some extent, if one member goes they all go," Leadbetter remarks. This system may closely resemble its ancient origins. "We're looking at a community that has been passed down from termite to termite for over 100 million years. It's fascinating to think about that. What makes termites so successful now is a slightly improved version of what made them so successful then."

Only the workers in a termite colony—comprising thousands to millions of individuals, depending on the species—have the specialized mandibles required to grind wood. Soldiers, whose jaw pincers are big enough to snip off the heads of ants or offending fellow soldiers, don't gnaw on wood, nor do molting juveniles or reproducing queens. They're fed a special cocktail by the workers, a nutrient-packed drop that exits through the posterior of the insect in a process called proctodeal feeding. "It's not feces. It's distinctly not that," comments Leadbetter. "Termites are exchanging this bolus, a drop of microbe-rich woodshake from a worker termite's rear end, periodically, all the time, so they're always sharing their microbes," he adds. That's how microbes populate the pristine guts of a growing young termite and proceed to digest its food. And digest it very well indeed.

When a wad of wood hits the termite's hindgut, the protozoa, spirochetes, and other microbes in there immediately get to work. They eventually convert more than 90 percent of the cellulose in their woody meal into the vinegar-like compound called acetate, which the termite absorbs and uses as fuel. On the way to churning out acetate, the

A termite's gut hosts a fairly efficient commune—almost 90 percent of the cellulose in the wood it eats is turned into its ultimate fuel, acetate. The process begins with protozoa, which ferment sugars into acetate. Other microbes then turn hydrogen (H_2) and carbon dioxide (CO_2) in the gut into either more acetate or into methane (CH_4).





Ethanol is society's desired biofuel, but for now, we can only make it from energy-poor sugars and starch in sources like corn or cane. Termite gut microbes turn energy-rich woody plant parts like xylan and lignocellulose into acetate, the termite's fuel, which society can't use. But the step from wood chips to simple sugars like pentose or glucose, which remains elusive, could be made through bioengineering.

microbes make a lot of hydrogen gas—about a third of the energy in the cellulose is released in this form—and carbon dioxide. Most of these gases are combined to form even more acetate, but the remainder is released as methane, which the insect can't use. Compare that to cows, for example, which vent as methane up to 20 percent of the energy in their microbially digested grassy meal. "Cattle lose basically a fifth of the nutrients in every mouthful as this energy-rich greenhouse gas," says Leadbetter. "Most termites release less than two percent, and oftentimes no methane at all." Still, multiply that by at least one quadrillion (picture 15 zeroes)

"We must continue investing in new methods of producing ethanol—using everything from wood chips, to grasses, to agricultural wastes."—Bush State of the Union, 2007

termites on the planet, and it adds up. "It's important to understand termites because of their role in the global carbon cycle, both as degraders of plant material and producers of methane. In total, they still contribute a fair amount of methane globally. But understanding the details of why they don't emit more is extremely important to understanding the greenhouse gas budget," says Leadbetter.

Carbon dioxide is another byproduct of termite life, released as the insect burns its acetate fuel. Which brings us back to what's in a microliter. "To try to understand the current system on the planet, you have to understand what's going on in this one-microliter environment," says Leadbetter. Up to two percent of the global carbon dioxide budget comes from insects we don't think twice about unless they're eating our house.

The magical fruit (or log)

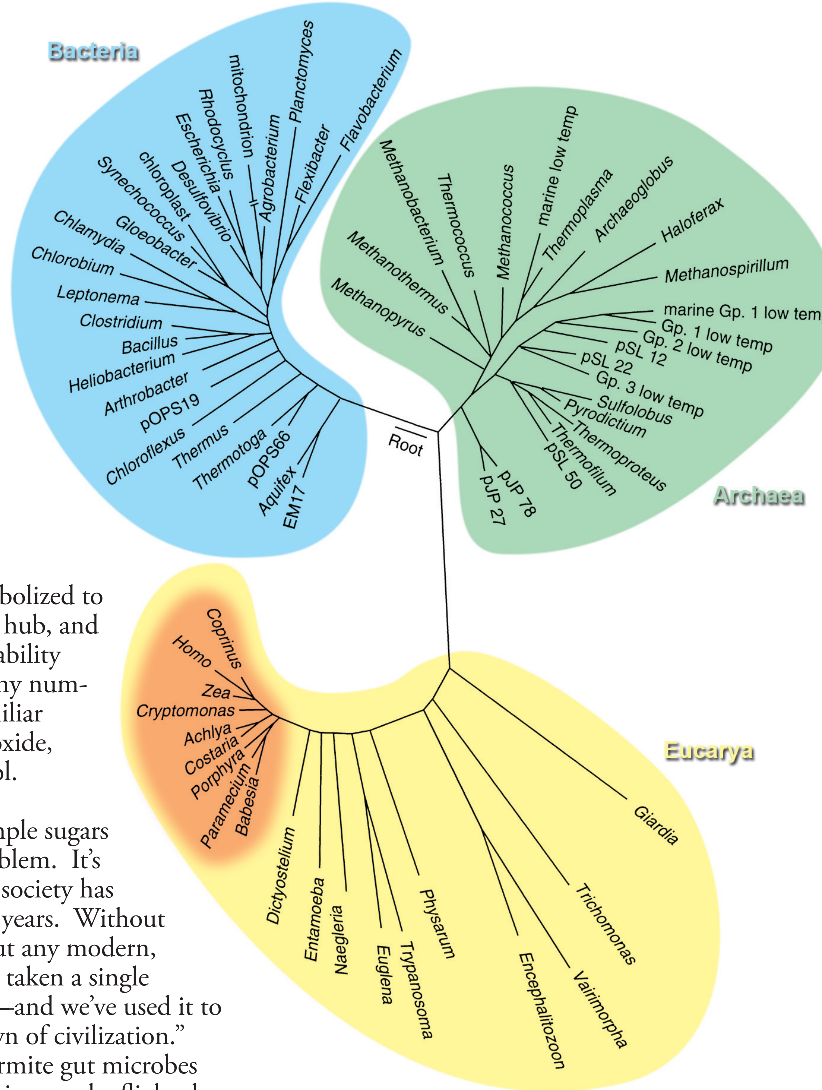
The same processes that provide energy to termites and ultimately lead to their portion of greenhouse gases may also help alleviate the human contribution to the same. Where Leadbetter sees microbes deriving fuel from a pine chip or a two-by-four for their hosts, many others see a potential bioalchemy that can fuel industries, homes, and cars. In his 2006 State of the Union address, President Bush announced that the government would begin funding research in "cutting-edge methods of producing ethanol, not just from corn, but from wood chips and stalks, or switch grass." In 2007 he reiterated, "We must continue investing in new methods of producing ethanol—using everything from wood chips, to grasses, to agricultural wastes."

Despite the promise of fuel from recycled sources, the primary source of ethanol is still corn. This summer will see the largest corn crop grown in this country since World War II, and, at 90.5 million acres, a 15 percent increase over last year's, states a U.S. Department of Agriculture report released on March 30. The cause for this boom, states the report, is the high demand for ethanol.

But the switch to renewable biofuels, or fuels derived from plants, comes with the usual problems and questions attendant to large-scale change. There are economic ones, like: Will farmers abandon other crops, like soybeans or cotton, in favor of profitable corn? Will the demand for corn-derived fuel then drive up the cost of food? In fact, we typically avoid consuming the most energy-rich plant parts—the woody fibers called lignocellulose—although these are potentially the best source for society's energy needs.

The route from wood chips, or any lignocellulose, to the final product of ethanol is short but crooked. Leadbetter equates it to an airplane flight with several potential hubs. From the plant source the route leads to simple sugars, such as

Life's diversity, once broken into only three kingdoms—Animalia, Plantae, and Fungi—is now recognized to be far more extensive. Bacteria and Archaea, which used to be lumped together, are as different from each other as they are from Eucarya, the multicellular organisms. Animals like humans (*Homo*), plants like corn (*Zea*), and fungi, together shaded in red, comprise what Caltech bioengineer John Doyle describes as only "a very nice hood ornament" on the car of life. Evolutionary distance, or how related one organism is to the next, is depicted by the length of the line that separates them.



Adapted from Pace, *Science*, vol. 276, no. 5313, pp. 734-40, 1997.

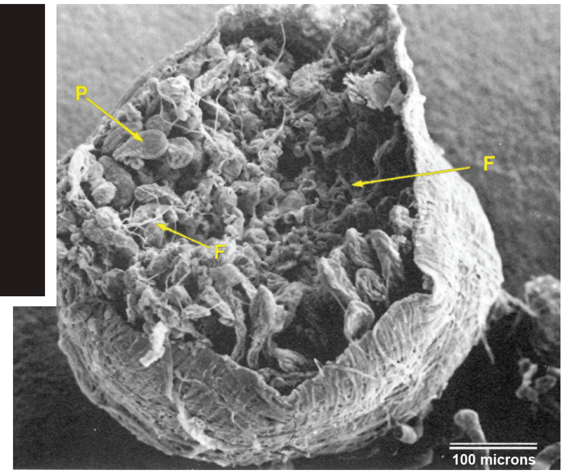
glucose. This sugar is metabolized to pyruvate, which is the next hub, and depending on oxygen availability the next flight can follow any number of paths to become familiar compounds like carbon dioxide, acetate, methane, or ethanol. According to Leadbetter, "We can convert simple sugars into ethanol at will, no problem. It's a modification of a process society has been performing for 3,000 years. Without genetic engineering, without any modern, sophisticated science, we've taken a single organism—the wine yeast—and we've used it to make ethanol since the dawn of civilization."

It just so happens that termite gut microbes are more interested in hopping on the flight that eventually lands at acetate, not ethanol. But they start from wood rather than a simple sugar, which is where Leadbetter's research comes into play. "There are many options at the level of pyruvate. It's been demonstrated several times over the last 25 years that we can engineer organisms to make ethanol from pyruvate. But what we're sorely lacking is the segment that might take us from a pine chip or rice hull or some other low-value plant lignocellulose source, to the level of a simple sugar or pyruvate. So we have to go to nature to come up with solutions to dismantle wood into its components."

Playing with Bugs

You probably learned in grade school that there are two, maybe three, kingdoms of organisms—plants and animals, and maybe fungi—but it turns out, as you might imagine, that this is a gross oversimplification of life's diversity. In the early 1960s, here at Caltech, Emile Zuckerkandl and Nobel Laureate Linus Pauling (PhD '25) revolutionized this staid view by introducing the field of molecular evolution, which allows scientists to map through genetic analysis the evolutionary history and development of complexity in organisms. Now, instead of three kingdoms, we see an array of branches on the tree of life, each one corresponding to "evolutionary time." On this tree, says Leadbetter, you see fungi, plants, and animals, but also a lot of other lines that are generally as long as those between plants and animals and fungi. When you zoom in, those three kingdoms, he says, "are what John Doyle here at Caltech described as being only 'a very nice hood ornament.' The car, of course, is the rest of the tree. The difference between *E. coli* and some of these other bacteria, for example, is as great as the difference between corn and ourselves. By extension, you might imagine that what these organisms can do, in terms of their physiology and their roles in the environment, is also very diverse." Life therefore clumps into three domains: eukaryotes (which include animals, plants, and fungi), bacteria, and

Photo by Tina Salmassi (MS ’98, PhD ’01).



From Breznak and Pankratz, *Applied and Environmental Microbiology*, vol. 33, no. 2, pp. 406–26, 1977.

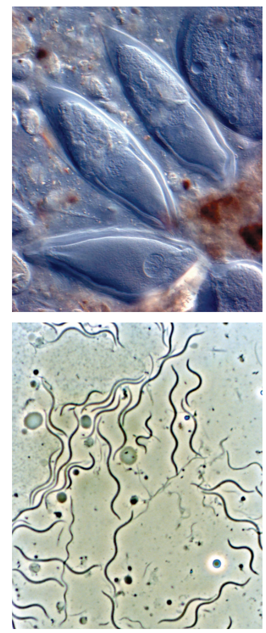
A view of *Zootermopsis* and its guts (above). The open gut (right), only 100 microleters in volume, is chock full of wood particles, protozoa (P) and bacterial filaments (F).

***Zootermopsis nevadensis* is Leadbetter’s termite of choice in California because it accessible and its gut microbes can be cultivated in the lab. Above, grad student Elizabeth Ottesen and Jian Yuan Thum (BS ’04) collect specimens from Mount Pinos, in the Angeles National Forest.**

archaea, which were once lumped in with bacteria but are now understood to be as clearly different from bacteria as they are from eukaryotes. “We live on a microbial planet,” says Leadbetter. He calls the termite hindgut “a playground of microbial diversity.”

By measure of both abundance and species diversity, termites are much more successful in the tropics, and comparatively few of their kind survive the harsh winters of northern New England and the Midwest. Leadbetter’s group studies two from among 2,600 species of termite in detail. He started with *Zootermopsis*, which basks in year-round comfort in temperate California. He compulsively looks for them, even when hiking with his family in the Angeles National Forest. “I turn over logs and peel back bark and see what’s on the other side. I think they find it annoying when I stop all the time. But they say you should never bring your work home with you,” he laughs. He brings it to his lab instead, filling Tupperware containers with *Zootermopsis*, an especially handy termite because it doesn’t mind lab life and its internal microbes are easily cultivated. “This allows you to not only pass through the intestinal zoo, but actually spend some time at some of the exhibits in a way you wouldn’t be able to otherwise,” he says. His group’s studies of the genes and pathways underlying *Zootermopsis* bacterial metabolism has most recently been aided in large part by a gene inventory-taker, known as a microfluidic device, whose development they pioneered at Caltech (see *E&S*, 2006, No. 4, p. 3).

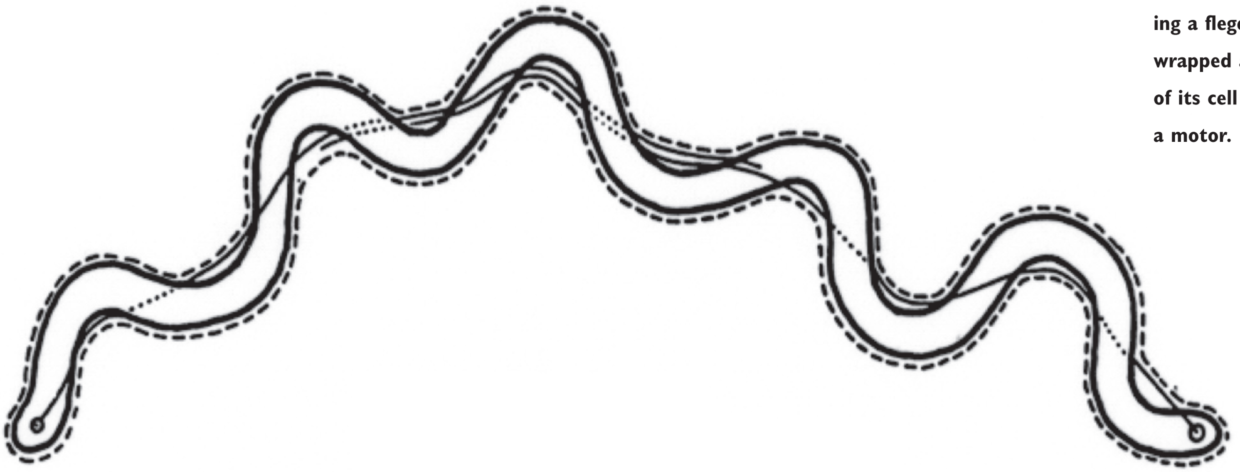
Half of a *Zootermopsis*’s weight is in its guts. Organisms from all three major domains of life reside in its hindgut paunch, which resembles our colon. A cross-section reveals what Leadbetter describes as “a cornucopia of microbes.” Most of the termite’s weight, therefore, is microbes and wood particles. Methane-making Archaea colonize the epithelium. In the gut fluid live seven species of protozoa that are found nowhere else in nature, and gene-based techniques have identified up to 100 different species of spirochetes, all of which happen to be closely related to *Treponema pallidum*, the bacterium that causes syphilis. But Leadbetter’s research has shown that in termites they’re symbionts, not disease agents. They’re complex, for single-celled organisms—they flex and swim with the help of a flagellar motor (see *E&S* 2006, No. 3, p. 6). The spirochete’s propeller, wrapped around the central region of the cell and encapsulated by an outer sheath, helps it generate enough torque to move in viscous environments that immobilize all other bacteria. “They hold the world record for being able to move at high viscosity,” says Leadbetter. His group cultivated one species, thereby learning that it consumes hydrogen and fixes carbon dioxide to make acetate.



Symbiotic microbes, at least for termites—protozoa (top) and spirochetes (bottom).

Although *Zootermopsis* microbes play interesting roles in wood degradation, and a billion dollars are spent on termite control and repair in South-

Adapted from Canale-Parola, *Bacteriological Reviews*, vol. 1, no. 1, pp. 181–204, 1977.



Spirochetes swim by flexing a flegellum, which is wrapped around the length of its cell and propelled by a motor.

ern California each year, this termite is only a bit player in the global carbon cycle. So Leadbetter took his research to the tropics, where termites rule. He and his collaborators delved into the microbial community of *Nasutitermes*, a native of Costa Rica, because, as he says, "both in number of species and number of individuals, they trump all other termites hands down." These he definitely can't bring home with him. "I have not even attempted to convince the USDA that this would be reasonable to do. In many places in the U.S., these termites would never make it through the winter, but I don't think you can guarantee that here," he says. So he studies the termites down there, and analyzes the data back in the U.S. Which is a good thing, because one Caribbean species of *Nasutitermes* recently made itself a happy new home in warm, humid Florida.

There are many zones in the guts of these Costa Rican termites, each with a different pH. They also host a completely different microbe population from that in *Zootermopsis*, most notably lacking the protozoa that digest wood in California termites. "So who's degrading the wood? Is it the bacteria? Is it the host?" Leadbetter wondered. To find out how it really works in *Nasutitermes*, Leadbetter joined forces with scientists Cathy Chang (BS '87), formerly of Diversa Corporation and now at the E. O. Wilson Biodiversity Foundation, Giselle Tamayo of the Instituto Nacional de Biodiversidad in Costa Rica, and Phil Hugenholtz and Edward Rubin of the Joint Genome

Leadbetter pulls open a *Nasutitermes* nest in a tree in Costa Rica (below). The streaks beneath his hand are termites jumping ship. *Nasutitermes* soldiers have nozzles instead of pincers (bottom). They spray their victims with terpenoids, an aromatic herbal substance that only annoys humans, but paralyzes ants.

Photo by Falk Warnecke, Joint Genome Institute.

Photo by Father Alejandro Sanchez.

Fluid from the guts of 200 termites (left) fills a tiny capsule whose genetic contents will be sequenced to determine the various roles of the termite's microbial community.

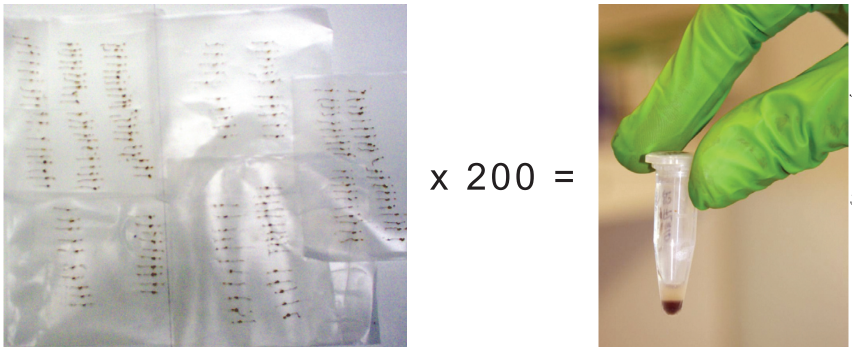


Photo by Falk Warnecke, Joint Genome Institute.

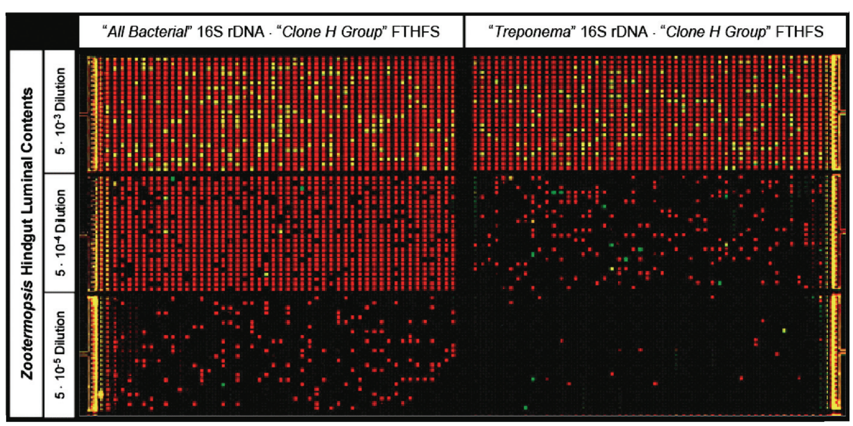
Institute. Together they are sequencing and analyzing the genes encoded by all 250 termite-gut bacteria species, most of which have never been studied before. They hope to eventually uncover what each is doing, catalytically speaking, especially when it comes to degrading wood. "This was a fairly risky project," says Leadbetter, because "the role of microbes in our local termites has been understood, to some degree, for about 100 years, but in these abundant tropical termites, there was no compelling evidence that their bacteria are involved in cellulose degradation."

When the results started coming in, "we breathed a big sigh of relief, because it turned out to be a gold mine in there," he says, and the details of the study will soon be published. "At least now we have a lot of genetic information—we don't know exactly what these genes do, but from similarities with other organisms in nature we can deduce their roles in one process or another. For the first time, we actually have a menu. We don't know how the meal is going to look when it's served, or how it's really going to taste, but at least we know the possibilities encoded in these genomes. It gives us some ideas, at the microbial level, of where they fit in the process of ligno cellulose-into-acetate conversion. And very simply, we didn't know that at all before," says Leadbetter.

Into the Future

The next step in producing ethanol from wood is more like a giant leap. Lignocellulose might be bioengineered into ethanol either by inserting ethanol-synthesizing genes into wood-degrading microbes, or by inserting lignocellulose-degrading genes into ethanol-producing yeasts or other organisms. It's too early to predict what will work in the end, says Leadbetter, "but at this

Leadbetter and his group pioneered a gene inventory technique that separates communities into single cells. This approach pinpoints the presence or absence of certain genes, like those that participate in making acetate (shown in green). At left is a full gut community, and at right the spirochete *Treponema*.



From Ottesen, et al., *Science*, vol. 314, pp. 1464-67, 2006.

stage, the idea is to think about how we might start assembling the components and organisms in new ways. Genome sequencing of microbial communities gives us many more possible components to work with," he continues. "If there's investment both at the university and the industrial level, I think there's no reason why we as a society cannot do this. This modularity in converting the ingredients into different products is real. It may be that within five years society will be able to convert some small amount of a pile of lignocellulose into some amount of ethanol at some rate. But what we really need is the ability to convert a large fraction into a large amount of ethanol or some other biofuel at a fast rate. And to be able to do so in really large volumes."

Despite its promise, Leadbetter is also concerned about complications that could arise. Is producing and burning biofuels rather than fossil fuels really better for the environment? The smell from modern ethanol production plants in the Midwest has been described as rubbing alcohol mixed with burning corn, and this pungent air is laced with carbon monoxide, carcinogens like formaldehyde and acetaldehyde, and smog-forming particles. Not only is corn a water- and fertilizer-hungry crop, ethanol production is itself a water-hungry process. A Minnesota study found that it takes more than four gallons of water—to ferment the corn meal and to cool the machinery—to make a gallon of ethanol. The wastewater, laced with hydrogen sulfide from the processing, is often dumped into nearby rivers. "It's a very complex issue, and I don't think the challenges we face with biofuels has been discussed all that realistically," says Leadbetter. "What will be the environmental impact of biofuel fermentation refineries? What will be the water demand? How sustainable will this really be?" Ultimately, he thinks several partial solutions will be necessary.

Leadbetter's immediate goals lie in a more focused direction. "I want to know everything there is to know about termites, their gut microbes, and how they make biofuels for their own use," he says. "To me it's mind-boggling: 250 species of gut microbes. Why not one? Why any at all? That's a teleological question, so you can turn it around and say 'What is the benefit for a system to have so many species? What are the mechanisms to come up with the best set of species—to kick out the losers, to acquire the winners, to improve? What has been the impact, on the organisms and the processes they catalyze, of over 100 million years of refinement of this system?' I think we're easily 25 years away from having what I consider to be a fundamentally sound understanding of this one-microliter environment, and that may be optimistic, to be honest." □

PICTURE CREDITS: 25, 28 — Jared Leadbetter; 28 — Andreas Brune

Look Up, Look Down, Look All Around

By Douglas L. Smith

Along with GPS receivers and DVD players, some luxury cars these days come with autonomous cruise control, which measures the distance to the car in front of you and automatically eases up on the gas if you start to get too close. Some versions will even hit the brakes for you. But they don't come cheap—Mercedes-Benz's Distronic Plus, for example, which incorporates two onboard radar units that stare straight ahead to different distances, costs about three grand. "A radar system consists of thousands of individual parts," says Professor of Electrical Engineering Ali Hajimiri. "A lot of that complexity arises from the fact that you are trying to pull information from one module to another one at very high frequencies through interconnects. Once you put everything on the same chip, you can actually eliminate a lot of the complexity." Hajimiri has done just that, creating a complete radar system that fits on the head of a thumbtack. Since we can put millions of transistors on a chip these days, the unit contains all the supporting electronics needed to send, receive, and process the radar signal, and even to sweep the beam back and forth. The chip was made with standard industrial processes, and in mass production would cost about a buck each, Hajimiri estimates.

The key, he says, was "a different approach. You can't just take a traditional, module-based design and simply transplant all of the modules onto the same chip. All of the elements had to be designed for this purpose. Very few people thought that solid-state technology could be used at very high frequencies, but we found ways of doing so and then combined it with digital signal processing. Up to then, integrated phased-array radar had been one of the last bastions of analog signal processing."

From left: Grad students Jay Chen, Edward Keehr, Aydin Babakhani (MS '05), Yu-Jiu Wang (MS '06), professor Ali Hajimiri, grad students Juhwan Yoo (BS '06), Florian Bohn (BS '01), Jennifer Arroyo, Hua Wang, and research engineer Sagguen Jeon (MS '04, PhD '06) create a phased array in Millikan Pond.

Guided Ripples, Focused Power

That the system is a "phased-array" radar means that, instead of being a dish that tilts, in the simplest case it's a line of dipole antennas, each one like an old-fashioned portable radio antenna. Such an antenna radiates its signal in every direction, like the ripples from a rock dropped from a bridge over a pond. But say that bridge had a line of people, armed with sticks instead of rocks, leaning over the railing. If one person poked the water, it would make a set of ripples as before. But if the next person poked the water an instant later—slightly out of phase, in other words—two sets of ripples would form. The overlapping ripples would add up in some directions and cancel out in others, making a new set that would travel at an angle determined by that fractional hesitation between pokes. Now, if everybody did this sequentially from left to right, in a sort of inverted version of the wave you see at sporting events, you could get a sizeable set of swells going, and if you altered the poke interval you could actually steer the waves from one bank of the pond to the other. Similarly, in radar, a phased array's beam is steered electronically by adjusting the phase of the signal at each antenna. There are no moving parts. "I can do that very fast, on the order of a nanosecond," says Hajimiri. "Or even faster, as the technology improves. I can have the beam pointing somewhere completely different the next nanosecond. No mechanical part can move nearly as fast."

A line of antennas can steer the angle of a beam across a plane, but a two-dimensional array can be steered in every direction, sweeping out the hemisphere in front of its radiating surface. Three-dimensional arrays are even possible, says Hajimiri. "Two-dimensional arrays generally make nice, narrow beams when you look straight ahead. But when you look sideways past a certain point, the beam widens. A three-dimensional array is uniform all over the place. And the three-dimensional array would generate a lot more power, because of all the antennas and the signal generators attached to them."

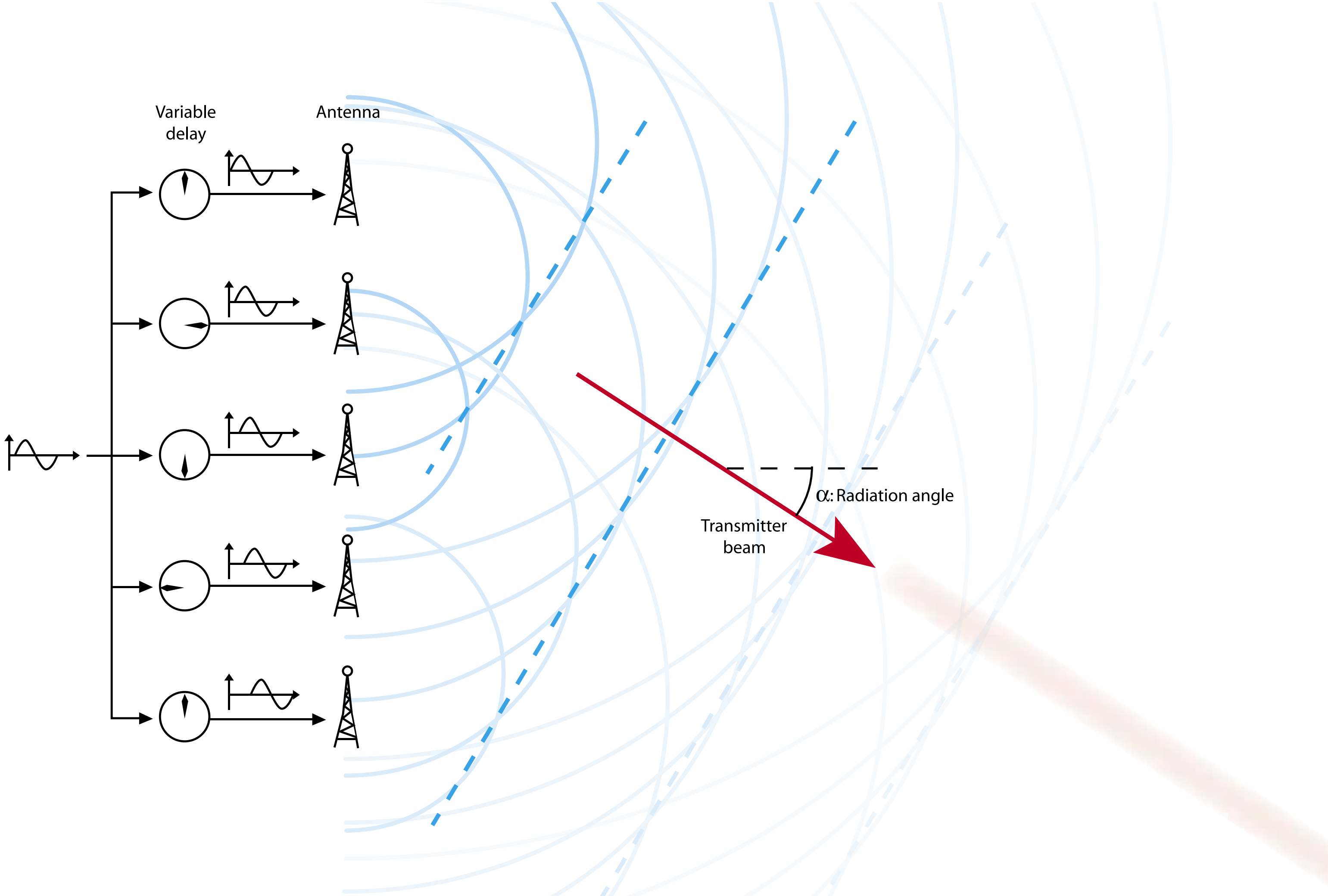
The phased-array concept has been around for quite a while—some antiballistic missile early warning radars of the 1960s used it, and the U.S. Navy's Aegis shipboard system has been operational since the '80s. But, says Hajimiri, "they're mostly used in airborne radar, because as you can imagine, you don't want any moving parts in an airplane that's going to pull 9 and 10 g's. As soon as you turn, you need a new antenna." A typical radar array in a fighter jet, nose-mounted to scan the skies in front of the plane, is about a meter square, several centimeters thick, and contains several thousand tiny antennas.

A tiny antenna puts out a tiny signal, but lots and lots of tiny antennas, properly synchronized, put out power in proportion to the square of their numbers. Even a piddling four-antenna array produces a sixteenfold increase in power over a single one—in the desired direction. It's like the difference between an ordinary light bulb and a laser—a classroom laser pointer is five milliwatts, or 20,000 times less powerful than a 100-watt desk lamp, but you don't need to point it at your eye to know which beam is brighter. This collective boost is vital, Hajimiri explains, because "the smaller the antenna, the less power, and the more antennas you need. So there's a tradeoff."

These airborne radars currently use expensive compound semiconductors, such as gallium arsenide microwave monolithic integrated circuits, which we civilians have in our cell phones' power amplifiers. Each module has one antenna and all its supporting electronics—the transmitter's power amplifier, the phase-delay controller, the low-noise receiver, and the receiver's gain control. The formidable problem of synchronizing the phase delays is handled by separate, highly complex (and very expensive) modules. These radars broadcast in the microwave band of the spectrum—whose wavelengths, confusingly enough, are actually a few centimeters long—at frequencies of around 10 gigahertz (GHz), or 10 billion cycles per second. Trying to coordinate a set of fixed delays for, say, a radar that always looks down toward the ground at a 60-degree angle to track the terrain, is tricky enough. If you want the beam to sweep, the system has to calculate variable time adjustments finer than a fly's eyelash all across the array. The slightest jaggedness, and the wavefront dissolves in chaos, like the din at a family reunion where everyone's talking at once. Internal travel times become critical, says Hajimiri. "If you try to connect parts with cables or leads, they have to match to hundredths or thousandths of a centimeter, and their lengths shouldn't change with temperature or variations in the electronics."

The Soviet Union's MiG-31 "Foxhound," which entered service in 1983, was the world's first production aircraft with an electronically scanned phased-array radar. With a forward range of 200 kilometers, it could track 10 targets simultaneously and engage four.

Courtesy of the Defense Visual Information Center



Steering Clear of Broadband Clutter

But the biggest civilian market for phased arrays is most likely going to be in broadband communications. The Federal Communications Commission recently opened up several bands, including the 24 and 60 GHz bands, for wireless communications systems. You might not think you could *get* any more networked, but just wait until your kitchen appliances need to talk to your Blackberry so that they can get your breakfast going super-early on the day of your big meeting. And when your microwave begins downloading Jon Stewart so that you can have something to stare at besides the instant oatmeal on the carousel (sure, you laugh now), we're gonna need a lot of bandwidth. Or consider the wireless office, with everybody's gadgets talking to each other all at once—as if we didn't have enough office clutter already.

The theoretical upper limit for information transfer at any given frequency increases with the broadcasting power. (Actually, to be accurate, it increases with the signal-to-noise ratio.) "At 24 GHz and 60 GHz we can get up to several gigabits per second on a few milliwatts of power over several tens of feet," says Hajimiri. "Your dial-up line is some 50 kilobits per second and your DSL is probably at best around one to two megabits per second. So this is another four orders of magnitude. If you can communicate at a couple of gigabits per second, you can transmit the entire contents of a DVD in about 10 seconds."

In such crowded airwaves, a steerable two-way communications beam has obvious advantages. Even a two-element phased array beats a single antenna, as anybody who has ever been to a loud party knows. Says Hajimiri, "If you're politely listening to a conversation which is getting quite boring, and there's a juicier conversation on the other side, you can tune into it while still nodding and looking like you're listening. The optimal antenna spacing in a phased array is half the wavelength, and for one kilohertz, which is kind of the middle of the audible frequency range, this works out to about 15 centimeters, which is more or less how far apart your ears are."

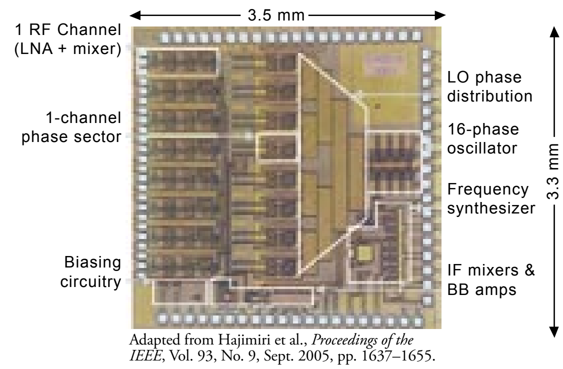
A phased-array cell phone would reduce the need for more ugly towers, and spare us from the feeble attempts to disguise them as trees. Each antenna in the array would pick up the incoming signal at a slightly different time. With the right delay at each antenna, all the signals coming from a certain angle would be in phase, amplifying themselves. But signals at the same frequency arriving from other directions would be out of phase, "and in fact they can cancel each other out if you design the delays right."

A phased-array transmitter (opposite page) takes an incoming signal (the sine wave at far left) and broadcasts it from each antenna in the array at a slightly different time. The sets of radiated waves from each antenna interfere with one another, creating a new set of waves that travels at an angle to the array. A phased-array receiver (below right) uses a similar delay to reassemble the original signal, amplifying it in the process.

Turning Silicon to Gold

"Silicon is truly today's alchemy," says Hajimiri. "It's a way of turning sand into money, quite literally. My philosophy is simple: if you can do anything in the digital domain, it should and will be done in the digital domain. And anything that can be done in silicon will be done in silicon. And most particularly, anything that can be done in CMOS should and will be done in CMOS." CMOS, for Complementary Metal Oxide Semiconductor, is an integrated-circuit manufacturing process that permits the fabrication of billions of transistors on a chip with a very high probability of all of them working. It is what makes today's PCs possible.

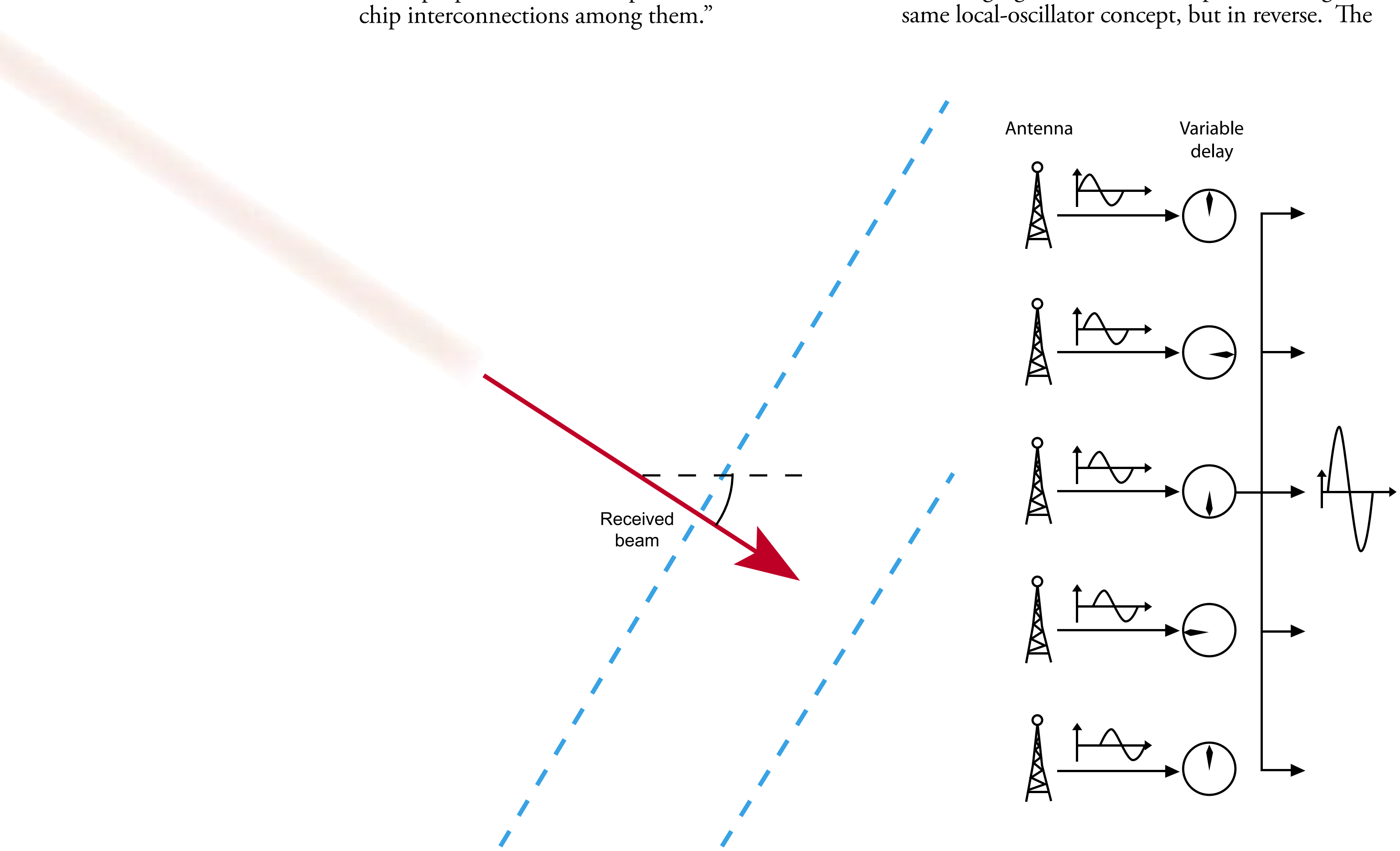
Doing everything on one chip gave the Hajimiri group a leg up on the thorniest problem—how to adjust the delay between antennas. The chip synchronizes the delays with a master clock circuit called a local oscillator, which can be built as a ring of amplifiers around which a pulse of voltage chases itself. Each lap takes one wavelength to execute, so by choosing the point in the loop where each antenna draws its time signal, you can steer the beam—in Hajimiri's case, by increments of 7.2 degrees. Says Hajimiri, "It's impossible to implement a local oscillator phase delay in a module-based architecture, due to the inevitable variations in the properties of the components and the off-chip interconnections among them."



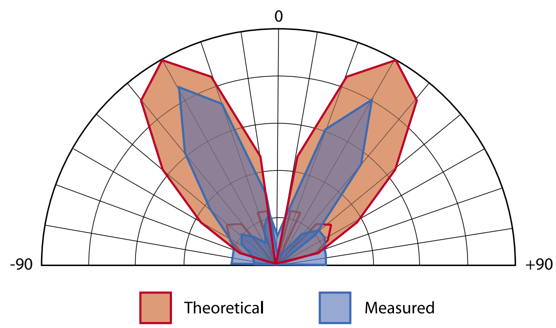
Adapted from Hajimiri et al., *Proceedings of the IEEE*, Vol. 93, No. 9, Sept. 2005, pp. 1637–1655.

The lab's first phased-array chip received signals at 24 GHz from eight off-chip antennas.

Hossein Hashemi (MS '01, PhD '04, now an assistant professor at USC) and Xiang Guan (MS '02, PhD '06) and Hajimiri created the lab's first successful device, built in 2003 and premiered at the annual International Solid-State Circuits Conference (ISSCC) in San Francisco in February 2004. This receive-only chip contained all the electronics needed to collect, amplify, and combine incoming signals in the correct phase—using the same local-oscillator concept, but in reverse. The

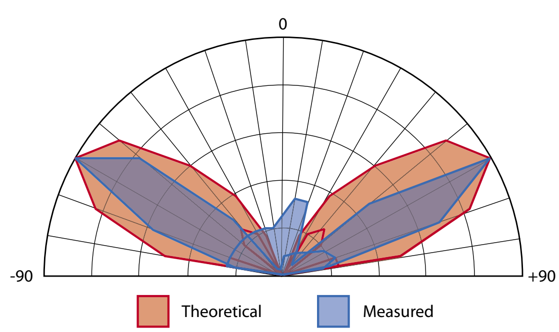


Even with only four antennas in use (the maximum the lab's testing equipment could accommodate), the receiver array's angular selectivity, shown here for a setting of either plus 30° or minus 30°, exceeded expectations. Data adapted from Hajimiri et al., *Proceedings of the IEEE*, Vol. 93, No. 9.



trio signed their work in the upper right-hand corner. "We tried to put in the Caltech logo," says Hajimiri, "but it was hard to lay out. You have to design chip elements as assemblies of squares, and there's software that combines them, but at the last minute the students said, 'We'd rather sleep after five days,' so they just put down Caltech." The plot above shows the array's theoretical and measured sensitivity to test sources placed at various angles. The chip had even better angular discrimination than predicted, as shown by the narrowness of the measured lobes.

Arun Natarajan (MS '03, PhD '07) and Abbas Komijani (PhD '05) and Hajimiri next built a four-element transmitter chip in 2004 that was unveiled at the 2005 ISSCC. The array gave a nice, tightly focused beam, as shown below. But a narrow beam counts for naught if you can't tell

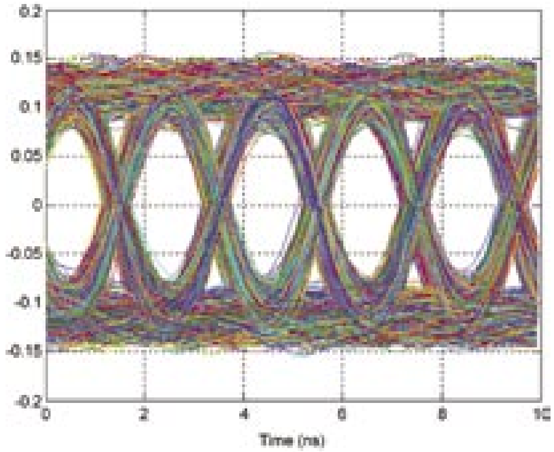


The lab's first transmitter chip, which also operated at 24 GHz, had four external antennas to match the testing apparatus. It, too, performed better than predicted. Data adapted from Hajimiri et al., *Proceedings of the IEEE*, Vol. 93, No. 9.

what's being sent. So the next test was to send actual data, in this case a random string of ones and zeroes, and see what came out. The results were plotted as an "eye diagram," so called because if you're looking at the output in an oscilloscope, the line should be at the top of the screen for a one and at the bottom for a zero. The middle should be blank, forming a wide-open eye. A squinting or closed eye reveals intermediate values, where the receiver will have to guess what was sent. At one gigabit per second, or actually 500 megabits per second per channel for two overlapping channels, says Hajimiri, "you can easily distinguish between all the ones and all the zeros. If I say, 'This is the cutoff line: anything below this is a zero, anything above it is a one,' I don't have to make any tough calls. This is considered a perfect eye—people who deal with eye diagrams are actually used to ones that are a lot less open."

In both these designs, the antennas were still off-chip components. There were two reasons for this—the size of the antenna is usually proportional to the wavelength, and a 24 GHz dipole antenna would be about three centimeters long, or 10 times the length of the chip itself.

But the other problem was more fundamental—silicon makes a lousy antenna. It has a very high dielectric constant, which means that it literally soaks up the radiating electromagnetic field. It's also a semiconductor, which means that it drains the incoming electric field away before it ever reaches the antenna. For an on-chip antenna, with silicon on one side and air on the other, fully 95 percent of the power leaks into the silicon. The group spent a couple of years playing around with several possible fixes, none of which worked particularly well. "In the end we said, 'If we can't get rid of it, we'll make it a feature,'" laughs Hajimiri. "We'll just redesign the system so the chip radiates from the backside." They essentially put the chip facedown in its mounting and let the signal travel in the direction it wanted to go anyway. They even



From Natarajan et al., *IEEE Journal of Solid-State Circuits*, Vol. 40, No. 12, Dec. 2005, pp. 2502–2514.

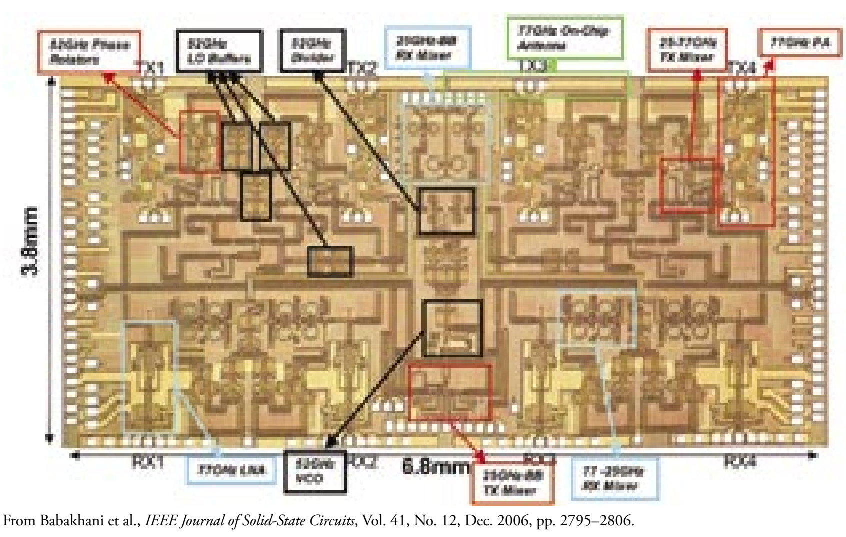
These colorful skeins are oscilloscope traces of digital data transmission from the 24 GHz chip at one gigabit per second. "Ones" are displayed along the top, and "zeroes" along the bottom; the crossovers happen when successive bits have opposite values.

turned this to their advantage by adding a silicon hemisphere to the back of the chip, now its front, to form a lens and improve the radiative properties of the antenna. The focusing effect gives the beam a longer range—up to 100 meters, says Hajimiri.

"In the end we said, 'If we can't get rid of it, we'll make it a feature,'" laughs Hajimiri. "We'll just redesign the system so the chip radiates from the backside."

Anything that helps boost the power output is a bonus, because if you apply too large a voltage to silicon circuits, you'll fry them, a phenomenon known in the trade as a low breakdown voltage. It doesn't take much of a voltage difference to convert a zero into a one in your PC, which is good because the less power you consume the less cooling you need. But broadcasting is a whole 'nother ball game. Explains Hajimiri, "The low breakdown voltage limits how much power you can transmit without killing the transistors, because it limits how large a voltage swing you can have in the circuit, and that determines how much power you can generate. So we had to find a way to use a large number of transistors, each one of them generating a little bit of power, and then combine all that power somehow."

But this had to wait until someone else had used all those transistors to make computers smart enough to help with the design. Radar frequencies are far above where other solid-state devices operate—Pentium chips, for example, run at a leisurely couple of gigahertz. Says Hajimiri, "Transistor performance has not been modeled very well at higher frequencies, and you're basically prone to the 'garbage in, garbage out' principle. If you don't know what you're designing with, you can't expect the product to be exactly like what you simulated." So the group spent close to a year developing a very accurate three-dimensional model of how the electromagnetic field propagates through the volume of the chip.



From Babakhani et al., *IEEE Journal of Solid-State Circuits*, Vol. 41, No. 12, Dec. 2006, pp. 2795–2806.

The 77 GHz model was the world's first phased-array chip to have it all—transmitter, receiver, and antennas—on one slab of silicon. The aluminum antennas, 600 millionths of a meter long and 50 wide, are the four golden bars running along the chip's top and bottom edges.

The model, which runs on multiprocessor PCs and can take several hours to execute, isn't perfect, either. Therefore Hajimiri's chips include self-correcting circuitry to account for performance variations in the individual transistors, as well as such external factors as temperature and humidity. "This is one thing I tell the students in my electronic design class every year—in integrated circuits, extra transistors are essentially free, so use as many as you want; use them any way you like. If it helps you, use them."

"Radio astronomy traditionally has been done with sparse, huge antennas. But if you can make them cheap, you can cover a very large area with a very large number of them—you could use an army of mice, or maybe ants, instead of an occasional elephant."

The group was now ready to put the transmitter, the receiver, and the antennas on the same chip. Natarajan and Aydin Babakhani (MS '05), Guan, Komijani, and Hajimiri spent 2005 working on a 77 GHz phased-array transceiver chip (consisting of about 15,000 transistors—peanuts compared to the tens of millions of transistors on a Pentium) that debuted, once again, at the ISSCC in 2006. The researchers used some of those transistors to simplify the design by having separate transmitter and receiver arrays—four antennas per—each with, again, all of their supporting circuitry. The chip has only two inputs: one to set the angle you want the beam steered to, and one for the data; ditto for the outputs. "That chip took about 10,000 man-hours of design time," says Hajimiri. "At 77 gigahertz, the antennas are small enough that we can put them on a chip. Putting a strip of metal on a chip is easy; putting a strip of metal on a chip that does the right thing is very, very hard. But by then we had figured out how to do it."

It's Both the Dessert Topping and the Floor Wax

With dirt-cheap send-and-receive units, you could put a whole bunch of them all over a car, and feed their outputs to a dashboard display that shows everything around you in 3-D, right next to the GPS screen. Better, to avoid sensory overload, "you could couple all those chips into a central system that does autonomous cruise control, self-parking, brake boosting, all of those kinds of features, in an integrated approach, instead of a patchwork of a little sensor here, a little sensor there, all doing different things, and not quite as well."

Lexus is touting the self-parking LS 460, on sale now. Parallel parking separates the wheat from the chaff in driver's ed, and some folks never truly master it. But in Lexus's TV spots, the driver pulls up next to a vacant space, pushes a button, and the car backs up, cuts the wheel, slips neatly into the slot, and then stops automatically. On the other hand, or perhaps the other foot, "brake boosting" is an electro-hydraulic system that keeps the brake lines as pressurized as possible for maximum stopping power when needed. The next generation of autonomous cruise control will tie into the booster controller so that if somebody cuts you off, the brakes will instantly clamp down hard at the slightest touch of the pedal. "And that's very important because most accidents—and I didn't know this until I started talking to the car companies—are caused by the fact that you don't apply the full force of the brake as soon as you see the problem, you just gradually increase it," Hajimiri says.

Which brings us to collision-avoidance systems, which are *not* coming soon to a dealer near you. On the most basic level, this could be a car telling a semi "DON'T CHANGE LANES! I'm right beside you!!" or two oncoming cars negotiating who is going to get out of the way based on their speeds, maneuverabilities, and surroundings. More advanced systems could allow emergency vehicles such as ambulances to part the traffic in front of them. "If you have a portable device that has beam-forming capability, you can both use it as a sensor and a communication device at the same time—it's both the dessert topping and the floor wax," Hajimiri says. "Car-to-car communication is quite important if you want to flock cars—group them into a flock and have them drive together. They have to talk to each other constantly." In fact, such a system would have to have all sorts of other sensors talking, too, about such things as tire pressure, for example—you wouldn't want a car in the middle of the flock to run over a nail and suddenly get a flat.

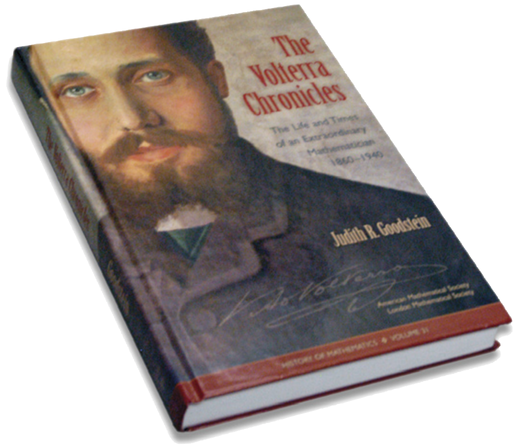
Hajimiri is now trying to generalize this approach into broader applications, such as scalable arrays. Scalable means that the entire surface of a car, an airplane, or anything could be tiled with chips that act in unison. Maintaining phase synchronization between all of these chips is an enormous technical challenge, and things get even more interesting if the surface is curved, as the surfaces of airplanes and automobiles tend to be. "The calculations are complex but doable," says Hajimiri. "They are somewhat similar to the calculations done for curved space-time, such as the differential geometric ones for general relativity." And it's well worth it, he adds, because of the tremendous power boost at the transmitter and the increased sensitivity of the receiver that results. James Buckwalter (BS '99, PhD '06, now an assistant professor at UC San Diego), Babakhani, and Hajimiri have developed a two-by-two scalable array that operates at 60 GHz.

Such arrays could crop up in all sorts of unexpected places, including radio astronomy. "Radio astronomy traditionally has been done with sparse, huge antennas. But if you can make them cheap, you can cover a very large area with a very large number of them—you could use an army of mice, or maybe ants, instead of an occasional elephant. You could have a square-kilometer array, or even larger, and you wouldn't have to use fancy cryogenic systems because of the phenomenal combined gain from all those antennas."

The group is also working on multiband, multibeam chips. Research engineer Sanggeun Jeon (MS '04, PhD '06), grad students Florian Bohn (BS '01), Yu-Jiu Wang (MS '06), and Hua Wang, and Hajimiri have built a phased-array receiver chip that can listen in on up to four beams at once, each at any frequency of your choice between six to 18 GHz.

Intel cofounder Gordon Moore (PhD '54) wrote a visionary paper in the journal *Electronics* in 1965. In it, among other things, he first made the empirical observation that has since become known as Moore's Law, which is usually quoted as saying that the number of transistors one can put on a chip doubles about every two years. Like Einstein's postulation of the existence of gravity waves, every prediction Moore made has come true—except, until now, for one. The final sentences read, "It is difficult to predict at the present time just how extensive the invasion of the microwave area by integrated electronics will be. The successful realization of such items as phased-array antennas, for example, using a multiplicity of integrated microwave power sources, could completely revolutionize radar." Beams Hajimiri, "I'm glad to tell you that we've done this 40 years after his prediction, and I'm glad Caltech did it. Gordon must be thrilled." □

PICTURE CREDITS: 32 — Mercedes-Benz; 34-35, 36 — Doug Cummings; 38-39 — Bob Paz



The Volterra Chronicles: The Life and Times of an Extraordinary Mathematician 1860–1940
by Judith R. Goodstein
The American Mathematical Society
310 pages, $47

Mathematician Vito Volterra was lucky enough to be born in the brief window of freedom for Italy's Jews that occurred between the liberation of their ghettos by the French and the beginning of Mussolini's fascist dictatorship. As Judith Goodstein writes in her biography *The Volterra Chronicles*, from the 1500s until the time of Volterra's birth, Jews were prohibited from, among other things, attending public schools at all levels (except for medical schools, so they could practice on other Jews), owning property, maintaining shops outside the ghetto, or remaining outside the ghetto after sunset. They had to wear a yellow armband, and they were restricted to a few trades. In contrast, Volterra, who was born in 1860, was free to pursue his passions of math and physics at the highest levels.

Volterra distinguished himself intellectually early in life—at age 13 he concocted an approximate solution to "the notorious three-body problem that had confounded mathematics since Newton's time," writes Goodstein. Despite his family's urging him to pursue a practical career like railroad engineer, Volterra seemed destined for academia. He was extremely gifted, but also charmed, winning a professorship soon after he earned his doctorate at the tender age of 23. This came at a time when most scholars toiled for a decade or more teaching high school or even junior high before climbing the university ranks. His best-known mathematical contributions are to integral and differential equations, but Volterra embraced all mathematical complexities that crossed his path.

This book is far more than the remarkable history of a man who remains extremely well known in extremely small circles. It is an exploration of Italian history, especially of its academic and political organization, from the late 1800s until the rise of Mussolini in the 1930s. Details like street addresses and their updated names today and descriptions of neighborhoods then and now give a sense of how people lived. Letters to and from Volterra intimately reveal his and his family's personalities, as well as how he and his colleagues dealt with one another.

In his lifetime, academics were also politicians and statesmen, and Volterra served as a senator as well as a lieutenant in Italy's Army Corps of Engineers during World War I. It must have hit him extra hard then when Mussolini enacted racial laws that mandated, among other things, that Jews could no longer attend public schools or universities or serve in Italy's armed forces. He died in this sad reality, shortly after World War II began. So as not to leave us dangling on this haunting note, Goodstein describes in the epilogue Italy's return to democracy and sanity and what happened to Volterra's Jewish colleagues and family, most of whom survived. She also provides the full text of Volterra's obituary by Sir Edmund Whittaker, which was a tribute to his life and work and was published in 1941 by the Royal Society of London. □—*EN*

Homer J. Stewart
1916 – 2007

Homer Stewart (PhD '40), a pioneer of rocket research who helped develop Explorer I, America's first satellite to reach orbit, died May 26 at his home in Altadena, California. He was 91.

A native of Dubuque, Iowa, Stewart earned his bachelor's degree in engineering from the University of Minnesota in 1936 and then came to Caltech as a graduate student in Engineering and Applied Science. He became interested in the rocketry work being done on campus by a small group of Caltech engineers and scientists, chief among them Theodore von Kármán. Stewart, von Kármán, and others began testing rockets in a rugged foothill area of the San Gabriel Mountains about five miles northeast of campus—a group of people and a site that would later become the heart of the Jet Propulsion

Laboratory.

Stewart joined the Caltech faculty in 1939, one year before completing his PhD in aeronautics. He taught both aeronautics and meteorology while also conducting research at JPL. His research interests included the rocket-exhaust velocity requirements for lifting a spacecraft into orbit and maintaining its trajectory. He also used his knowledge of fluid flow to explore wind-driven energy. In the late 1930s, he and von Kármán built a wind turbine on a summit known as Grandpa's Knob in the mountains of Vermont. The machine generated up to a megawatt of power, and operated through World War II in cooperation with a local electrical company. The project was abandoned after the war, in part because fossil fuel became so available and cheap.

As chief of JPL's research analysis section, Stewart participated in many rocket projects, including the WAC Corporal, the Corporal, the Sergeant, and the Jupiter C. He was the chief of JPL's liquid propulsion systems division when JPL and the Army Ballistic Missile Agency (now the Marshall Space Flight Center) developed and launched Explorer I in January 1958.

During a two-year leave at the just-formed NASA, he served as director of planning and evaluation, and recommended what would become the Apollo missions to the moon. He also suggested Cape Canaveral as the launching site for putting rockets into orbit. He received the NASA Exceptional Service Medal in 1970.

Stewart served on the Caltech faculty until his retirement in 1980.

He is survived by two daughters, Barbara Mogel of Chesapeake Beach, Maryland, and Kay Stewart of San Diego; a son, Dr. Robert J. Stewart of Burien, Washington; two sisters; a brother; and two grandchildren. □

Felix Strumwasser 1934 – 2007

Felix Strumwasser, an early explorer in the field of neurobiology, died from cancer on April 19. He was 73.

Strumwasser's career spanned five decades, and he was active in the lab until the end. He was born in Port of Spain, Trinidad, on April 16, 1934, and started college at UCLA at age 15. After earning a bachelor's degree in zoology at age 19, he went on to his doctoral degree in neurophysiology and zoology, also from UCLA, in 1957.

Strumwasser arrived at Caltech as an associate professor in 1964 after a brief time as a lab scientist first at the National Institute of Mental Health, then at the Walter Reed Army Institute of Research. He also taught a neurobiology summer course from 1964 to 1969 at the Marine Biological Laboratory (MBL) in Woods Hole, Massachusetts.

During his 20 years at Caltech, Strumwasser headed a research program in neurobiology, focusing on the mechanisms of sleep as well as investigating procedures for measuring cellular activity. He also studied circadian rhythm and how neurons are stimulated and store information. His findings are still frequently cited and continue to pave the way for advances and research in the field.

After he left Caltech in 1984, Strumwasser taught physiology at Boston University's School of Medicine and then returned to MBL three years later, where he directed the neuroendocrinology lab until 1992. From that time until just before his death, he combined his neurobiology background with a burgeoning interest in human behavior as a professor and researcher of psychiatry and neuroscience at the Uniformed Services University of the Health Sciences in Bethesda. He also served as a program director for the National Science Foundation's Division of Integrative Biology and Neuroscience.

He is survived by his close friend Phyllis; four sons; a daughter; and five grandchildren. □

MILDRED G. GOLDBERGER
1934 – 2006

Mildred Goldberger, wife of Marvin "Murph" Goldberger—Caltech's president from 1978 to 1987—died September 11, 2006. She was 83.

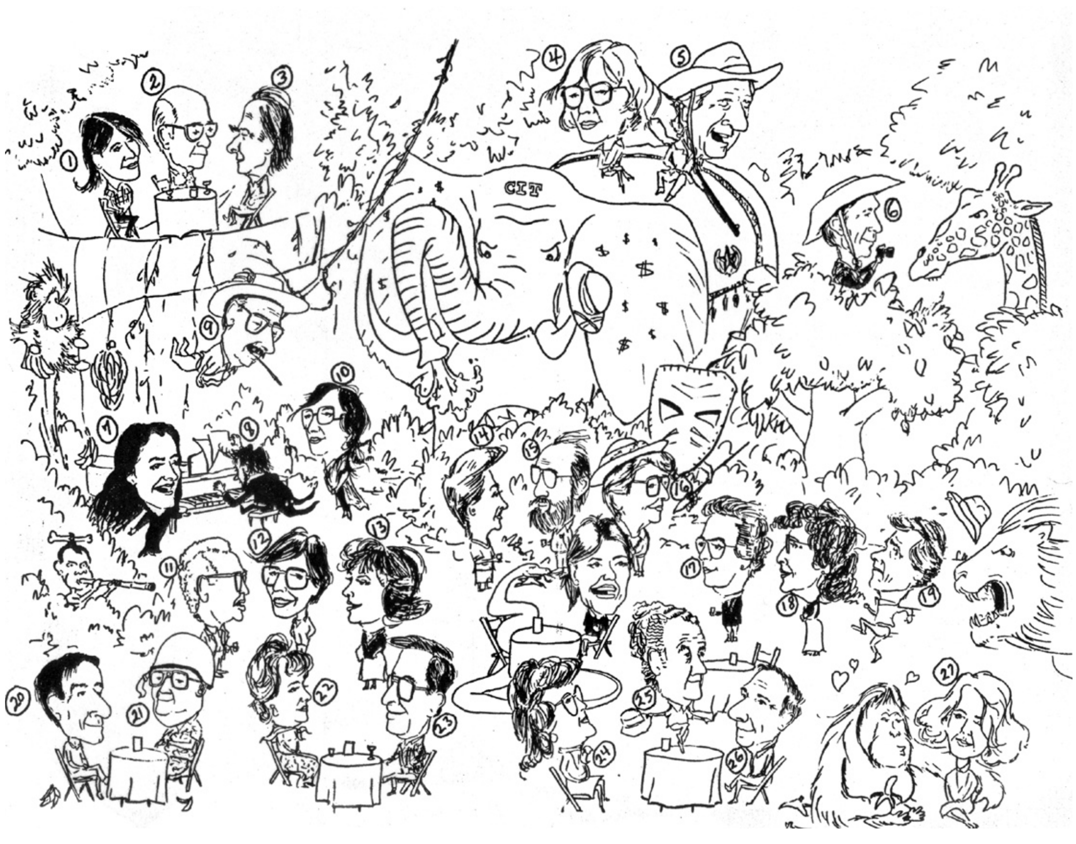
As Caltech's "first lady," Goldberger was an avid gardener, an enthusiastic supporter of the Women's Club, and a skilled hostess. She also edited the *Los Angeles Times* column "Scientific View," for which she solicited contributions from female scientists and science writers.

Born Mildred Ginsburg in Wichita Falls, Texas, on March 26, 1923, Goldberger received a BA in mathematics from the University of Illinois in 1943 and then went on to do graduate work in math, physics, and economics at the University of Chicago. During her time there at the height of World War II, she was a research assistant for the theoretical physics division of the Manhattan Project.

Among other jobs, Goldberger served as chief of the computation group for the University of Chicago Air Force Project, course manager for the math department at Princeton University, economics instructor at Rutgers University, research analyst with the New Jersey Department of Higher Education, and research associate with Princeton's Center for Environmental and Energy Studies, all before she arrived at Caltech in 1978. The topic of the environment was dear to her, and she addressed it in her column. In one op-ed piece written in 1981, Goldberger broke down the pros and cons of using solar energy, a term gaining currency and sorely abused.

A colleague, Faculty Associate in History Judith Goodstein, described Goldberger as a head-turner, with platinum hair and unabashedly bold and outsized black-framed eyeglasses that matched her personality. According to those who knew her, her laugh was breezy, her mind inquisitive, and her opinions passionate. Her columns, about science and scientists, addressed serious themes with a good dose of humor, and she ignored the surgeon general's warnings about cigarette smoking. "I doubt that she charmed the trustee wives, but perhaps that was part of Mildred's charm—she was the quintessential, outspoken, unscripted, candid first lady of the campus who only marched to her own drummer," says Goodstein.

Goldberger was a staunch advocate for women and helped found the Organization for Women at Caltech. In one column in 1981, she declared women better suited for space travel than men—they are smaller and lighter, more dexterous, and can handle equipment with delicate precision, she wrote—and encouraged them to shrug off the "time-worn stereotype" of timid dependence. But she also took her "first lady" duties seriously, as Charlotte Erwin and Romy Wyllie recalled in their book *The President's House at the California Institute of Technology*, which depicts Goldberger presiding with panache over countless formal teas for Caltech Associates and faculty wives. She used freshly grown



The guests at the Wasserburgs' tropical-themed good-bye party for the Goldbergers were immortalized in this cartoon. How many do you recognize? Check your answers at right.

herbs and edible flowers from her garden in many of the exotic meals she and her husband cooked from scratch and served at dinner parties at their home.

Indeed, food sparked what Goldberger called an epiphany about her Jewish heritage, which she also wrote about. She grew up in a town she described as "just a wide place in the road before oil was discovered," where "very few people had ever actually seen a Jew, let alone lived alongside one." It wasn't until her first visit to family in Chicago during spring break at college, when she accompanied them to temple services, that she embraced her heritage. "People were helping themselves from enormous trays of pastries like none I had ever seen," she wrote. "In the Protestant world where I grew up . . . you were supposed to pretend not even to look when you took just the nearest piece from the plate." Her enthusiasm for quality food and good humor was evident at the small au revoir to the Goldbergers on May 25, 1987, at the home of MacArthur Professor of Geology and Geophysics Gerald Wasserburg—who was also chair of the Division of Geological and Planetary Sciences—and his wife, Naomi. The 27 guests were told to bring good company, no serious presents, and lots of "Banana Republic banality and style to the send-off of the Top Banana and the Pineapple Queen." The hosts and their helpers were rumored to have cooked for three days straight to prepare an authentic Indonesian banquet, with every herb, spice, and condiment researched. A "foodie" long before the word was introduced, Mildred blessed the feast, praised the kitchen staff, and ate with the style and gusto that marked her presence at Caltech.

Goldberger is survived by her husband; sons Samuel and Joel; and grandchildren Nicole, Natalie, and Natasha. □

1. Judith Goodstein 2. Norman Lear 3. Richard Feynman 4. Mildred Goldberger 5. "Murph" Goldberger 6. John Hopfield 7. Cynthia Blum 8. Arie Michelson 9. G. J. Wasserburg 10. Marie Morrisroe 11. Murray Gell-Mann 12. Lydia Matthews 13. Gwyneth Feynman 14. Susan Goldreich 15. Stanley Sheinbaum 16. Naomi Wasserburg 17. Betty Sheinbaum 18. Shirley Cohen 19. Barclay Kamb 20. Peter Goldreich 21. David Morrisroe 22. Dianne Epstein 23. David Goodstein 24. Cornelia Hopfield 25. Samuel Epstein 26. Marshall Cohen 27. Linda Kamb

Kanamori Wins Kyoto Prize

Hiroo Kanamori, the Smits Professor of Geophysics, Emeritus, has been awarded Japan's top honor, the Kyoto Prize, by the Inamori Foundation. The foundation was established in 1984 by Kazuo Inamori, founder and chairman emeritus of Kyocera and KDDI Corporation, to award those who "strive for the greater good of society."

Kanamori is one of the world's leading authorities on earthquakes, and is widely known for many important contributions to the field, including the moment-magnitude scale, devised in 1977, which determines the magnitudes of very large earthquakes based on the amount of energy they release. Using the improved method, Kanamori assigned more precise magnitudes to large earthquakes of the past, like the 1960 Chilean earthquake, which he determined to be the world's largest known earthquake at a moment magnitude of 9.5. Kanamori also contributed to the understanding of tsunamis, in particular the relationship between ground motion and the giant sea waves generated by it. He has long been an advocate of automated early-warning systems to alert populations to a seismic event that could result in a tsunami. Kanamori will receive a cash gift of 50 million yen (approximately $410,000), a medal of 20-karat gold surrounded by emeralds and rubies, and a diploma, and will be feted at a special weeklong event in Kyoto beginning November 9. He plans to donate half of the award money to Caltech's Seismological Laboratory and the other half to Japanese earthquake relief funds. □

Goldreich Gets Shaw Prize

Peter Goldreich, the DuBridge Professor of Astrophysics and Planetary Physics, Emeritus, has been named winner of the $1 million 2007 Shaw Prize for astronomy by the Shaw Prize Foundation of Hong Kong. The prize is awarded each year to four recipients in the fields of astronomy, life sciences and medicine, and the mathematical sciences. Goldreich was cited by the foundation for his "lifetime achievements in theoretical astrophysics and planetary sciences." Goldreich's work has addressed fundamental phenomena such as the dynamics of planetary rings, pulsars, interstellar masers, the spiral arms of galaxies, the rotation of planets as well as their orbital resonances, and the oscillations of the sun. He has explored a range of topics, from why Saturn's rings have sharp edges, to how stars send out coherent microwaves, or masers, in a manner similar to lasers on Earth, to how the moon Io affects the radio bursts of Jupiter. He is currently focusing on planet formation and turbulence in magnetized fluids. □

Honors and Awards

The Sperry Professor of Biology and investigator with Howard Hughes Medical Institute **David Anderson**, the Mettler Professor of Engineering and Applied Science **William Johnson** (PhD '75), and the McCone Professor of High Energy Physics **Mark Wise** have been elected members of the National Academy of Sciences. Election to the academy is considered one of the highest U.S. honors in science and engineering.

Jacqueline Barton, Hanisch Memorial Professor and professor of chemistry, has been awarded the 2007 F. A. Cotton Medal for Excellence in Chemical Research by the Texas A&M Section of the American Chemical Society and the university's department of chemistry. The honor recognizes her contributions to molecular biology, particularly her intercalation techniques for the study of DNA. A director of Dow Chemical, Barton has also been named an Outstanding Director for 2006 by the Outstanding Directors Exchange for her role in creating the post of chief technology officer at Dow.

Mike Brown, professor of planetary astronomy, has been awarded the Richard P. Feynman Prize for Excellence in Teaching in recognition of "his extraordinary teaching ability, his skill in exciting his students, and his evident caring about his students' learning."

Charles Elachi (MS '69, PhD '71), Caltech vice president, director of the Jet Propulsion Laboratory, and professor of electrical engineering and planetary science, has been selected by the Aerospace Historical Society to receive its 2007 International von Kármán Wings Award. The award recognizes him for his exceptional leadership at JPL as well as related distinguished technical contributions to the nation and its aerospace industry. He has also been elected to the National Academy of Engineering's governing council for a three-year term.

Leroy Hood (BS '60, PhD '68), visiting associate in biology and president of the Institute for Systems Biology, has been elected to the National Academy of Engineering, which cited his "invention and commercialization of key instruments, notably the automated DNA sequencer, that have enabled the biotechnology revolution." Hood also received one of the first-ever Science Education Advocate Awards of Washington State LASER (Leadership and Assistance for Science Education Reform), along with the **Laser Interferometer Gravitational-Wave Observatory** (LIGO) in Hanford, Washington, created by Caltech and MIT.

Ken Hudnut, visiting associate in geophysics, has been named one of "50+ Leaders to Watch" by *GPS World* magazine, which has been covering the global-positioning industry since 1989. A geophysicist and project chief with the U.S. Geological Survey, Hudnut manages the GPS L1C modernization project and is geodesy coordinator for the U.S. Department of the Interior.

Alexander Kechris, professor of mathematics, gave the ninth annual Paul Erdös Colloquium at the University of Florida on May 7.

The Troendle Professor of Cognitive and Behavioral Biology, Professor of Computation and Neural Systems, and Executive Officer for Neurobiolgy **Christof Koch**, the Hayman Professor of Aeronautics and Mechanical Engineering **Michael Ortiz**, the Harkness Professor of Economics and Political Science **Charles Plott**, and the Brown Professor of Theoretical Physics **John Schwarz** have been elected to the American Academy of Arts and Sciences. Founded in 1780 by John Adams, John Hancock, and other scholar-patriots, the academy "undertakes studies of complex and emerging problems."

Stephen Mayo (PhD '87) has been named Bren Professor of Biology and Chemistry, effective February 1. He is also an investigator with the Howard Hughes Medical Institute and became an executive officer for biochemistry and molecular biophysics in 2004.

Hiroshi Oguri has been named Fred Kavli Professor of Theoretical Physics, effective February 1.

Edward Stone, Morrisroe Professor of Physics and vice provost for special projects, has received the Philip J. Klass Award for Lifetime Achievement as part of *Aviation Week*'s 50th annual Laureate Awards. The Laureate Awards recognize achievements in aerospace, aviation, and defense. A principal investigator on nine NASA spacecraft missions and coinvestigator on five others, Stone has served as project scientist for the Voyager 1 and Voyager 2 deep-space probes since 1972. He has also served as director of the Jet Propulsion Laboratory. □

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