e&s

Engineering & Science

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VOLUME LXXIV, NUMBER 2, SPRING/SUMMER 2011

California Institute *of* Technology

ON THE COVER

Did *E&S* run amok at our local home and garden store? We're not saying, but there is method in our madness. This eclectic collection encapsulates some of Caltech's research efforts to break the world's addiction to fossil fuels. Curious? **Turn to page 13.**

DEAR ALUMNI AND FRIENDS OF CALTECH,

Caltech has always been drawn to the biggest challenges, in terms of difficulty and in terms of potential impact on society. Energy represents both. Energy drives economic development and improves the quality of our lives. However, utilizing conventional sources of energy comes at an ecological cost. We need to shift the goals of science and technology from promoting progress to promoting *sustainable* progress.

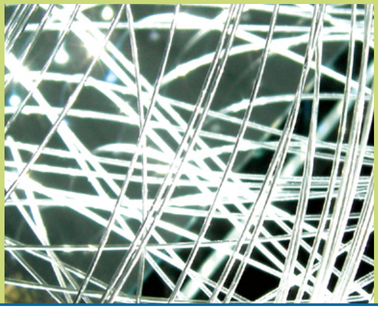
This issue of *E&S* tells many stories about how Caltech is putting the full force of its creative intellect, collaborative method, and tenacious spirit behind building a sustainable future. A powerful combination of public and private support allows Caltech researchers to explore revolutionary new ways to harness clean energy and make it available on a terawatt scale. We also practice sustainability on campus so that the Caltech innovation engine runs as powerfully yet efficiently as possible, providing a model for other organizations and a source of inspiration for our students.

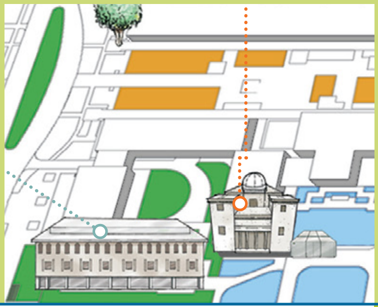
Several of the projects discussed in this issue orbit the new **Resnick Sustainability Institute** (resnick.caltech.edu), which is creating synergies among research in several disciplines in order to find transformative energy solutions. Resnick is also partnering with the new Joint Center for Artificial Photosynthesis, a DOE-sponsored Energy Innovation Hub. Other featured initiatives show what happens when Caltech takes on solar, wind, and biofuel energy challenges, as well as the creation of a "smart grid" that uses such energy more efficiently.

Caltech's sustainability strategy involves more than discovery in our research labs. We also integrate sustainability into the way we manage our physical infrastructure, as you will see in a special centerfold map featuring the various green initiatives around campus. Caltech and other universities perform as laboratories of innovation in developing new sustainability strategies that can then spread out to surrounding communities and society at large. Welcome to the Campus Green 2.0.

Jean-Lou Chameau
President

Stewart and Lynda Resnick





Far left: This bundle of optical fibers will carry sunlight to subterranean spaces in the renovated Linde + Robinson Laboratory forGlobal Environmental Science.

Left: This adaptive reuse of a former astrophysics building is just one example of how Caltech's physical plant is becoming a green plant.

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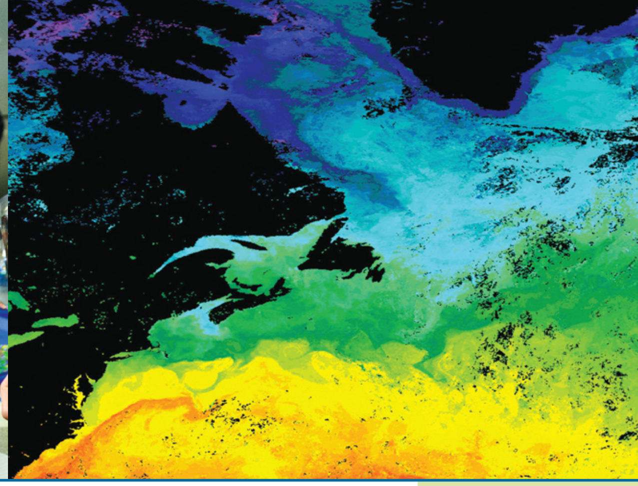

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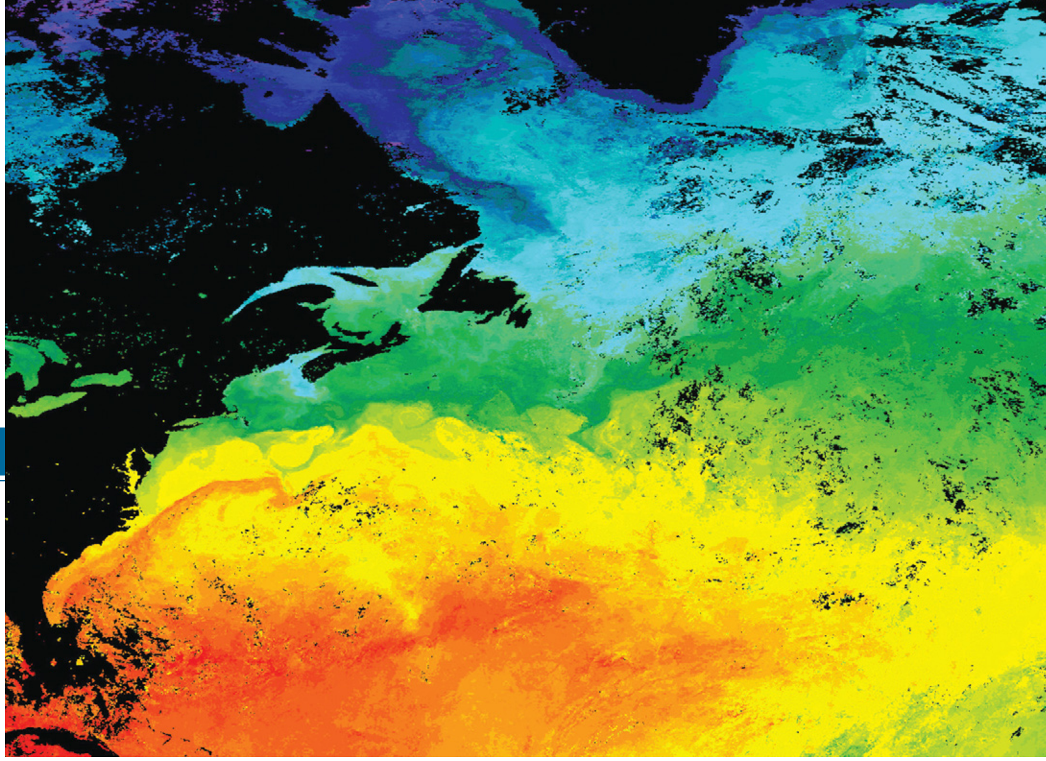

WARM WATERS, COLD WINTERS

If you're sitting on a bench in New York City's Central Park in winter, you're probably freezing. After all, Manhattan's average January temperature is 0°C. But if you were just across the pond in Porto, Portugal, which shares New York's latitude, you'd be much warmer—the average temperature there is a balmy 9°C.

Throughout northern Europe, average winter temperatures are around 10°C warmer than at similar latitudes on the northeastern coast of the United States and the eastern coast of Canada. The same phenomenon happens over the Pacific, where winters on the northeastern coast of Asia are colder than winters in the Pacific Northwest.

Caltech researchers have now discovered an explanation for these chillier winters. The culprit? Warm water. "Warm ocean waters off a continent's eastern coast actually make it colder in the winter—it's counterintuitive," says Tapio Schneider, the Gilloon Professor of Environmental Science and Engineering. Schneider and postdoc Yohai Kaspi described their work in a paper published in the March 31 issue of the journal *Nature*.

In the Northern Hemisphere, subtropical ocean currents circulate in a clockwise direction, bringing an influx of warm water northward from the low latitudes. In the Atlantic, the Gulf Stream originates off the Florida coast and moves north along the Eastern Seaboard before turning eastward near the coast of North Carolina and heading out into the ocean.

For decades, the conventional wisdom has been that the Gulf Stream heats northern Europe by delivering warm water from the Gulf of Mexico. But in 2002, research showed that the Gulf Stream doesn't transport enough heat to be directly responsible, contributing to perhaps 10 percent of the temperature contrast between the continents.

Now Kaspi and Schneider have found that the temperature difference isn't because the Gulf Stream warms Europe, but because the Gulf Stream *cools* the eastern United States. Their computer simulations of the atmosphere show that the warm water heating the air above it leads to the formation of Rossby waves—atmospheric undulations that stretch for more than 1,000 miles. These Rossby waves are stationary—their peaks and valleys don't move, but they still transfer energy, drawing cold air down from the northern polar region to form a plume just to the west of the warm water. In our case, this dumps the frigid air right over the northeastern United States and eastern Canada.

The researchers then sped up Earth's rotation to see how this affected the dynamics. When they did, the plume of cold air got bigger—consistent with it being from a stationary Rossby wave. Most other atmospheric features would get smaller if the planet were to spin faster.

Although it's long been known that a heat source could produce Rossby waves, which can then form plumes, this is the first time anyone has shown that this can affect continental temperatures. The researchers say the cooling effect could account for 30 to 50 percent of the temperature difference across oceans.

This process also explains why the cold region is equally big in North America and Asia, despite the two continents being so different in topography and size. The Rossby wave–induced cooling depends on heating air over warm ocean water. Since the warm currents along both the Pacific and the Atlantic's western boundaries are similar, the resulting cold regions farther west would be similar as well.

The next step, Schneider says, is to build simulations that more realistically reflect what happens on Earth by incorporating such complexities as continents and clouds. —*MW* E&S

This map shows sea-surface temperatures averaged over eight days in September 2001, as measured by NASA's Terra satellite. Dark red represents warm water (32°C) and purple is cold (–2°C). The Gulf Stream can be seen as the orange strip extending from the eastern U.S. toward the Atlantic.

PICTURE CREDITS
2 — Ronald Vogel, SAIC for NASA GSFC; 3 — Genping "Roots" Liu; 4, 10 — Lance Hayashida; 5 — Charles Decker; 7 — Katie Neith; 9, 11 — Jenny Somerville

WALL OF SOUND

Over 50 members of the Caltech Jazz Bands and the Caltech-Occidental Concert Band brought the sound of music to the Great Wall of China in March. Positioned in front of a fort on a portion of the wall near Beijing, the group played a concert featuring two new pieces written specifically for the occasion. One of the world premieres was written by Caltech alumnus Leslie Deutsch (BS '76, MS '77, PhD '80), chief technologist for the Interplanetary Network Directorate at JPL; the other was written by his son, Elliot, a jazz bandleader, composer, and trumpeter. The featured vocal soloist, Kjerstin Williams (BS '00, MS '02, PhD '06), lent her voice to the jazz tunes. The group also joined fellow musicians from Tsinghua University for a joint concert in Beijing. —*KN* E&S

"Playing on and climbing the Great Wall was definitely a highlight of the trip. It will be something that I will be able to talk about for decades after I graduate from Caltech, since it will always stand out from the everyday life of a Techer," said freshman clarinetist Hima Hassenruck-Gudipati.

'MID THESE DANCING ROCKS

The following real-world paradox comes to you courtesy of Assistant Professor of Geology Michael Lamb: "Say you're out hiking, and you come to a roaring stream plunging down the side of a mountain. It's full of rocks and boulders, all precariously balanced. You come back the next year, and you find that those same rocks are still there, just where they were. In fact, year after year you come back, and they never seem to move. Why is this?"

Don't know the answer? Neither does Lamb, and he's been thinking about it for a long time. Loose rocks on the bottom of lazy, low-sloping rivers migrate slowly downstream under nature's inexorable nudging. But in very steep channels, where it would seem that the collaboration between water and gravity should produce much more dramatic results, much of the stuff on the bottom stays put. And no one knows why.

A huge flume recently installed on the Caltech campus just might provide some answers. A flume is an artificial river—in this case, a tilted rectangular chute down which water cascades. Explains Lamb, "We can load our flume with various sediments, including fair-sized rocks, tilt it at any angle up to 15 degrees, and change the rate of flow of the water. That gives us a way to simulate all kinds of rivers."

Rocks, water, slope—surely there must be more to simulating a river than that? "Surprisingly, that's complicated enough," shrugs Lamb. "Water, on its own, we understand fairly well. We know the equations that describe how it flows in a smooth channel. But as soon as we start introducing sediment, the coupling between moving sediment, immobile sediment, and water becomes quite a complicated problem. We don't even know the equations to describe it."

The flume hulks in one corner of the Central Engineering Services building's machine shop, filling virtually every cubic inch of available space. It features a main section more than 15 meters long and, bone-dry, it weighs

15 tons—simply dwarfing most of the other laboratory flumes in the world capable of such steep slopes. Lamb didn't design it this way from a bigger-is-better mentality, but because he's interested in complexities that can't be modeled on smaller scales. "Imagine a steep mountain stream where the boulders have organized themselves into steps," he explains. "There's a boulder that makes a little waterfall, with a pool at the bottom, and below that there's another boulder making another waterfall with another pool, and so on. In order to understand how the sediment organizes itself into these structures, and how the structures then feed back into the system, we'd need to create three or four step-and-pool sequences in a row. You can't do that in a small flume."

A remotely controlled cart trundles back and forth atop the length of the flume, bearing high-precision instruments that map both the surface and the bottom of the artificial river with submillimeter accuracy. Water overflows into the flume's upstream end from the headbox, which is constantly refilled at whatever rate is needed in order to simulate anything from a trickling creek to a roaring cascade. The headbox is replenished from the tailbox at the flume's downstream end by a pair of pumps. "The larger one is the size of a Volkswagen," Lamb points out. "It can move 8,000 gallons of water a minute."

"Typical flume research," Lamb continues, "uses sand or even finer sediments, which can be pumped right through the pipes along with the water. But we're looking at the much coarser objects found in mountain channels." Rocks the size of softballs or soccer balls don't normally mix well with high-speed pumps, so a system of external conveyors collects the accumulation in the tailbox and returns it back to the head.

Lamb's plans range from studying issues of local concern, such as how debris rumbles down a denuded mountainside after a wildfire, to the global connection between erosion and climate change. "When you weather silicate rocks into clays, you're sucking carbon dioxide out of the atmosphere. But once the rock is covered by a layer of clay, the weathering process shuts down unless you physically transport that material away and expose fresh bedrock to more weathering. So the highest chemical weathering rates are tied to the highest erosion rates. In the Himalayas, for example, where rocks are uplifting rapidly and the rivers are eroding rapidly, weathering may be drawing enough CO_2 out of the atmosphere to affect global climate. But if I stood in front of a mountain river with the most knowledgeable people in the world, and asked them to tell me how fast that river was cutting, or how much sediment would come out of it in a year, they wouldn't be able to tell me within a factor of ten. We just don't have the observations yet to know how these systems work.

"A lot of research has been done on low-sloping, big channels: how to engineer them, how to dam them, and so forth. That makes sense, because we live in a world full of cities built on rivers. But small, steep mountain channels play a critical role in shaping our terrain and climate over long timescales, and we know very, very little about them." *—DZ* e&s

A look into the empty flume. The flume can be tilted as much as 15 degrees, allowing water and sediments—such as rocks, pebbles, and dirt—to flow down and simulate everything from a creek to a cascade.

Laura Decker scores a hit on the Air Force Academy's Heather Nelson at the NCAA saber finals in March.

ON THE FENCE

Life is about making choices, but this one's a doozy: Laura Decker, a senior who recently changed course from chemistry to medieval history, is on the threshold of an even bigger decision—grad school or the Olympics? Yes, *those* Olympics: trying out for the U.S. fencing team for the 2016 summer games in Rio de Janeiro.

Decker has dreamed of being a scientist since the seventh grade, she says. Her plan was to get a PhD and go into research, and she got off to a flying start at Caltech—by the summer of her sophomore year she was immersed in synthetic organic chemistry as a SURF (Summer Undergraduate Research Fellowships) student in the lab of Nobel Prize–winner Robert Grubbs.

Meanwhile, she'd also signed up for fencing to fulfill her phys ed requirement. Although she'd never wielded a blade, she'd studied martial arts in high school, and before the first class ended, she found herself on the Caltech varsity squad. "My high school was probably the only one in the entire state of New Jersey that didn't have a fencing team," she says. "But that's the great thing about Caltech athletics—no experience required. If you show up and you work hard, you're on the team." Of course, natural aptitude helps. Decker got serious about saber in May of her sophomore year, and as a junior she qualified for the NCAA finals, competing in the 2010 national championships at Harvard. (Only 42 colleges nationwide have fencing teams; since it's an individual sport, there are no divisions as there are for sports like basketball.)

"I traveled a lot, fencing on the national circuit, and met a lot of people," Decker recalls. "By the end of January in my junior year, I realized that I couldn't see myself being stuck in a lab for the rest of my life." She opted for history that spring and, with the collegiate season over, competed in United States Fencing Association (USFA) tournaments, where she earned points toward qualifying for the Olympics.

But earning match points and making the team are two very different things. Training to be an Olympian isn't something you can do between problem sets, nor is it something you can do in Braun gym, as good as Caltech coach Michael D'Asaro is. Says Decker, "If I wanted to train seriously, I would need to decide to do so before entering a PhD program, as fencers tend to physically peak in their mid-twenties." But with no experience training full-time for a sport, she wondered if it was worthwhile putting academia on hold to pursue something this far-fetched. Meanwhile, applications for graduate school were coming due; if the athletic regimen proved too much after a few months, she'd have lost a full year of academics.

Fortunately, there's a grant for that: Once a year the Caltech Y hands out the Paul Studenski Memorial Award, a travel grant for up to $4,000 intended for a student at a crossroads in life who, in the words of the endowment letter, "would benefit from a period of time away from the academic community in order to obtain a better understanding of himself and his future." When Jeanette Studenski wrote that in the fall of 1974, female undergrads were just starting to appear on campus; the Studenskis' son, Paul (BS, MS '72), had been killed in an automobile accident that summer while driving to Cornell to begin graduate school, after having taken a year off to clear his head while seeing the country.

Decker was trying to figure out what to do when she "got one of those emails that goes out to everybody. I don't read them very often, but this one looked like one I might be interested in." The email invited potential Studenski applicants to an information session and dinner at Caltech Y board member Tom Mannion's house. Says Decker, "I felt like I was at a crossroads, but I wasn't sure that this was the sort of crossroads the committee was looking for. A lot of the awards in the past have been for more humanitarian kinds of things." However, her dinner companions convinced her to apply, and as you may have guessed, she is this year's winner. Says Caltech

Y board member Deborah Smith, who sat at Decker's table, "If Laura's situation wasn't a crossroads, I don't know what is."

Will fencing triumph over (or even delay) academia? It's anybody's guess. This past March at the NCAA finals at Ohio State, Decker beat Caitlin Taylor of Brown (5-4), a member of the Australian national team. That was the good news. The bad news is she lost 5-4 to Dagmara Wozniak of St. John's, who is ranked second in the United States and 18th in the world, and who brought home the bronze from Beijing as part of the 2008 Olympic team. Decker also lost 5-0 to Monica Aksamit of Penn State, ranked sixth in the country—but in January Decker had defeated Aksamit 5-2 at an Olympic-qualifying USFA event. NCAA tournaments use a round-robin format, with the top four fencers going on to the direct-elimination finals; Decker did not make the cut. "Last year was my first major tournament, and I was completely freaked out," she says. "This year I was more competitive in all my bouts."

And if the saber proves mightier than the pen, there's still one last crossroads Decker will have to face. A dual citizen of the U.S. and the U.K., she notes: "I could make the British national team, but they're not as strong as the U.S. team. To make the U.S. team, I'll really have to work." *—DS* E&S

HOUSE OF THE POWERING SUN

The house of tomorrow won't just be green—it'll be smart. At least that's how students at Caltech and the Southern California Institute of Architecture (SCI-Arc) envision it. For over a year, the joint SCI-Arc/Caltech team has been designing and building its vision: a state-of-the-art, energy-efficient house for the Solar Decathlon.

Sponsored by the Department of Energy, the biennial competition challenges 20 teams from around the world to create the most energy-efficient, affordable, and attractive house possible. The teams will be judged on 10 "events," in each of which the house has to perform certain tasks, such as heating 15 gallons of water in less than 10 minutes. The houses also have to cost less than $350,000 for the consumer. The competition will take place from September 23 to October 2 on the National Mall in Washington, D.C., providing a high-profile venue intended to inspire policymakers, industry leaders, and the public to pursue a sustainable future.

Designed for use in the urban landscape of Southern California, the SCI-Arc/Caltech house is full of energy-saving features. The exterior is covered with a soft, insulating "skin" of white architectural vinyl, making the building somewhat resemble a giant pillow. The house is entirely powered by solar panels, and plentiful windows make artificial lighting during the day unnecessary. Waste heat produced by the air-conditioning unit generates hot water and provides warmth at night. "This is a simple idea that makes a lot of sense, but hasn't yet been done in a residential setting," says Richard Wang, a senior majoring in mechanical engineering who is spearheading Caltech's side of the project. The key aspect that sets this house apart from other Decathlon entries, he says, is that the team based every design choice on rigorous theoretical and computer models of how a house works. The team is installing and testing its designs this summer.

The next challenge will be transporting the entire house to Washington, D.C. The house consists of four modules that will sit on flatbed trailers and be pulled by trucks across the country. When everything arrives on the Mall just before the competition, cranes will piece the modules together like a jigsaw puzzle. One of only two houses in the competition with two stories, the SCI-Arc/Caltech design boasts a spacious interior, despite an area of only 800 square feet. (Contest rules limit the area to between 600 and 1,000 square feet.) The four modules' open interiors become a single, roomy structure, providing comfort that turns a house into a home, says Fei Yang, also a senior majoring in mechanical engineering and another student leader. In many of the other designs, he says, the modules remain separate, looking like trailers. "I don't care how pretty your trailer is," he remarks. "It's still a trailer."

The house's brains are an off-the-shelf computer called Control4, which controls everything from appliances to heating. The computer keeps track

The full-sized mock-up of the SCI-Arc/Caltech Solar Decathlon house is partially covered in a soft, insulated "skin" of architectural vinyl.

of the house's energy balance, making the necessary adjustments to ensure net-zero energy use—that the house consumes no more power than it produces—over the course of the competition. Future residents can set the washer to have their laundry done by Sunday, and the machine will turn on when it's efficient and cheap to do so—at night after a sunny Saturday afternoon, for example. They can even use their iPad as a remote.

They will always be able to override the computer, so there's no worry of the house becoming self-aware and turning into HAL, the homicidal machine from *2001: A Space Odyssey*. "Our house is not meant to control your life, but to help you live your life," says Yang. All the fancy technology in the world won't make a greener globe unless people change how they live, he says.

Because people living in the SCI-Arc/Caltech house will be able to monitor their energy efficiency in real time, they can adjust their behavior accordingly—a phenomenon sometimes known as the Prius effect, in which drivers of the hybrid car alter their driving styles to improve mileage. The team is trying to maximize this effect by considering such notions as installing "mood lights" that change color depending on energy consumption.

The team is also working on lights that can be dimmed or switched on and off with just simple gestures. But despite the high-tech wizardry, the house of a greener future is closer to realization than you think, Wang says. "The Solar Decathlon—and our house in particular—is standing proof that affordable, beautiful net-zero houses are already here." —*MW* E&S

E/Q PHONE HOME

Pity the poor news anchor in the immediate aftermath of an earthquake. While he's waiting on the feed from the Caltech Seismo Lab, there's precious little for him to do, apart from restating the obvious ("If you've just joined us, there was an earthquake moments ago"), offering unassailable prognostications ("Aftershocks are certainly a possibility"), and taking breathless phone calls from chatty viewers ("Nah, this one was definitely stronger than Northridge, because this time *both* my cats freaked out").

The banalities and generalities will no doubt be with us forever. But that thoroughly unscientific community survey may soon change into something much more useful.

What if there were inexpensive, pocket-sized gizmos that could sense the shaking and zap that info to Seismo while the ground was still rolling? What if you could deploy a million such devices throughout Los Angeles, forming an incredibly dense sensor network?

Oh, wait—this gizmo already exists. It's your cell phone. There's an accelerometer built right into it; add a bit of software, and you've got a portable seismometer. Instead of a grainy image of a major earthquake collected from widely scattered recording stations, seismo-smart phones could give first responders a high-definition, block-by-block (or even floor-by-floor) picture of how buildings and soil are moving.

So says Ramo Professor and Professor of Computer Science K. Mani Chandy. He's helping develop the Community Seismic Network (CSN), a proposed city-scale system

that would link low-cost sensors with a cloud-computing network. The CSN's detailed maps would allow emergency crews to be dispatched *where* they're most needed *when* they're most needed immediately after the quake. Says Rob Clayton, professor of geophysics, "In a quake, one building may be destroyed while the building standing next to it is not damaged at all. We saw examples of this in the Mexico City quake. The CSN enables the community to build a highly detailed shake map collaboratively, giving first responders much more accurate information." Clayton is the principal investigator on a grant from the Gordon and Betty Moore Foundation to deploy a prototype network of some 1,500 sensors throughout Pasadena.

In between earthquakes, the CSN has other uses. Tom Heaton (PhD '78), professor of engineering seismology and another PI, proposes to put dense sensor networks into high-rise buildings, with many sensors on each floor. "Being able to monitor a building's behavior over long periods of time will help civil engineers better understand its dynamics," he says. "Add to that a dense network of ground sensors, and seismologists and civil engineers can work together on unraveling the interaction between ground soil mechanics and building mechanics."

"It's a nontraditional way of doing seismology and civil engineering," acknowledges Monica Kohler (PhD '95), a senior research fellow in mechanical and civil engineering. Earlier this year, she and a group of students did a preliminary test in the nine-story Millikan Library, the tallest building on campus. The students distributed a dozen smart phones throughout the building and on the roof. A Caltech staffer videoing the event for posterity contributed a Caltech beaver-mascot bobblehead and a cup of water to the rooftop sensor array, and then the shaking machine, an off-axis rotary contraption that has long been a staple of Caltech's earthquake engineering studies, was loaded with weights and set spinning. Small ripples immediately appeared in the water.

Graduate student Ming Hei Cheng (MS '09) explains: "Although there's only about 500 pounds of weight in the shaker, the rotation makes it act as if it were 5,000 pounds. And here on the roof is where we'll feel the maximum acceleration and the maximum displacement." In fact, the entire nine-story building was moving as much as a couple of inches from side to side—easy enough for the sensors to detect. (The bobblehead remained motionless.)

The CSN is an integral part of a year-long course on distributed systems being cotaught by Chandy and Julian Bunn, a lecturer in computing and applied mathematics, along

Monica Kohler (in the yellow shirt) supervises the deployment of smart phones on the roof of Millikan Library. Also in the photo: grad student Shiyan Song (MS '09).

with grad students Michael Olson and Matthew Faulkner. Besides the Moore Foundation, the project is being supported by the National Science Foundation's Cyber-Physical Systems Initiative, and by Google, which donated 20 Android phones. The other CSN team members include project manager Richard Guy, computational scientist Leif Strand, grad student Annie Liu (MS '10), undergrads Rishi Chandy and Jonathan Krause, and Andreas Krause, assistant professor of computer science and the third PI. Says Chandy, "The project is typical of Caltech's multidisciplinary approach to research, with undergraduates, PhD students, staff, and faculty from different areas collaborating to solve real problems that impact humanity."

But the CSN won't rely solely on smart phones. The experiment on the Millikan rooftop also tested several freestanding miniature sensors, each the size of a half-dollar, that can be plugged into a desktop computer. Arming a PC with one of these devices, at a cost of about $100 each, makes it possible to record several months' worth of motion data. "Everybody's got a computer," remarks Kohler. "So we could distribute hundreds of thousands of these. And in ten years, everybody will have a smart phone."

So right after that next big temblor, when a new crack has appeared in your driveway and you've just got to tell everyone, don't be in such a hurry to grab that cell phone. It may have already beaten you to it. —*DZ* E&S

EARTHSHAKING NEWS

In the wake of the magnitude 9.0 Tohoku earthquake off the northeastern coast of Japan, reporters sought the expertise of Caltech's seismologists. Representatives from approximately 50 different media outlets—television, radio, newspapers, and online publications—descended on the Seismo Lab, where Caltech and U.S. Geological Survey (USGS) staff were on call for around-the-clock interviews. (The Pasadena USGS office is, not coincidentally, just across Wilson Avenue from the Seismo Lab.) In the weeks following the disaster, Caltech experts were a consistent source of reliable data and judicious opinions. Jean-Philippe Avouac, professor of geology and director of the Tectonics Observatory, disseminated the latest data from the quake; Hiroo Kanamori, the Smits Professor of Geophysics, Emeritus, who had been in Tokyo at the time, offered firsthand accounts of his experiences; and Mark Simons, professor of geophysics, penned an op-ed for the *Wall Street Journal* on the importance of federal funding for advanced early-warning and response technologies. Caltech faculty and staff were quoted in over 250 articles and broadcast reports. —*KN* E&S

Above: At a press conference held on March 11, just over 12 hours after the quake and resulting tsunami, USGS and Caltech seismologists fielded questions from a throng of reporters. From left: Ken Hudnut, a USGS visiting associate in geophysics; Tom Heaton (PhD '78), professor of engineering seismology; Lucy Jones, also a USGS visiting associate in geophysics; and seismologist Kate Hutton, a member of the professional staff.

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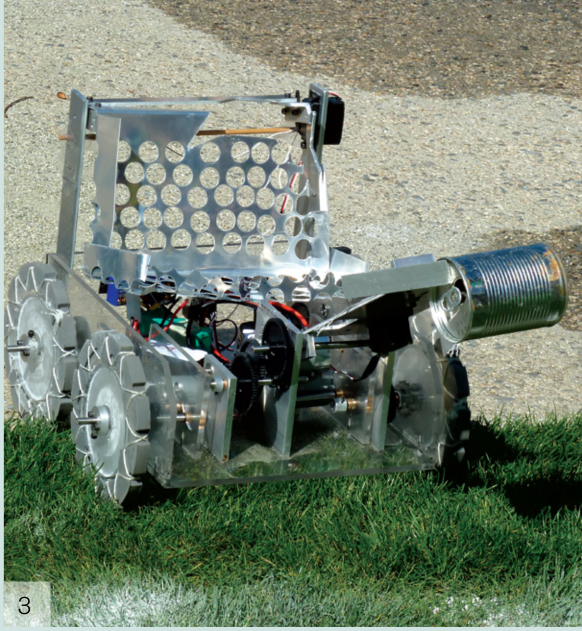

ROBOTS REUSE, RECYCLE

For the past 26 years, robots have invaded Caltech each spring to battle for their makers' bragging rights—sometimes to an electronic death—in the ME 72 engineering design competition. On March 8, six teams of undergrads competed in an "Extreme Recycling" challenge that pitted pairs of robotic vehicles against difficult terrain and other robots in an effort to collect plastic water bottles, aluminum cans, and steel cans. Each team built two robots designed to traverse water, sand, rocks, and wood chips to gather the recyclables and drop them into recycling bins—or prevent their opponents from doing so. The competition was the culmination of a 20-week laboratory class in which each team was given a budget of $1,200 to build the best bots possible. The final designs followed a couple of basic themes: robots with scoopers and grippers to grab the bottles and cans, and ones with baskets to haul the loot. Other design features included ramps to wedge under opponent robots and trip them up. The winning team, named BRB, consisted of juniors Chris Hallacy, Brad Saund, and Janet Chen. Team BRB bested all five other teams without dropping a heat during the double-elimination contest. —*KN* E&S

1 ME 72 participants check out one of the "placebos," robots designed by the teaching assistants and used to round out a bracket when there was an odd number of contestants. Placebos were not allowed to score, or to intentionally hurt another robot, but could generally mess with the competition. This placebo featured an innocent-looking, rainbow-colored pinwheel that was actually made of magnets.

2 Pile up! Competing robots ram into each other like sumo wrestlers in an effort to neutralize the opposition.

3 A winning robot from Team BRB shows off its can-carrying skills.

4 The giant placebo robot menaces a much smaller competitor.

5 A Team Aviator robot takes a spin through the water trap, successfully picking up a can along the way.

6 This daring run threatened to damage the electronics. Juniors Sara Ahmed (left) and Jee Su Baek blow-dry the robot before its next round. (The third team member, senior Cole Hershkowitz, is not pictured.)

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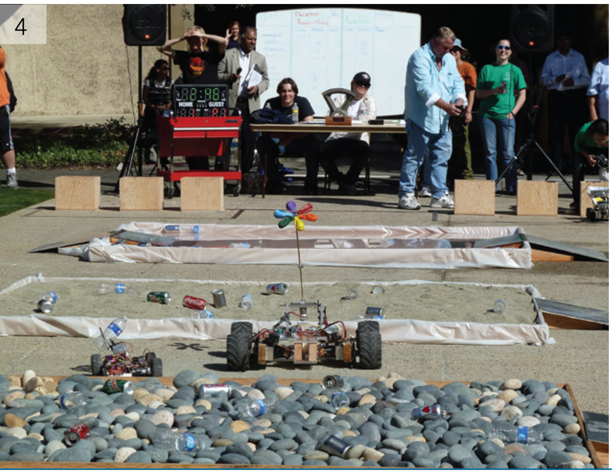

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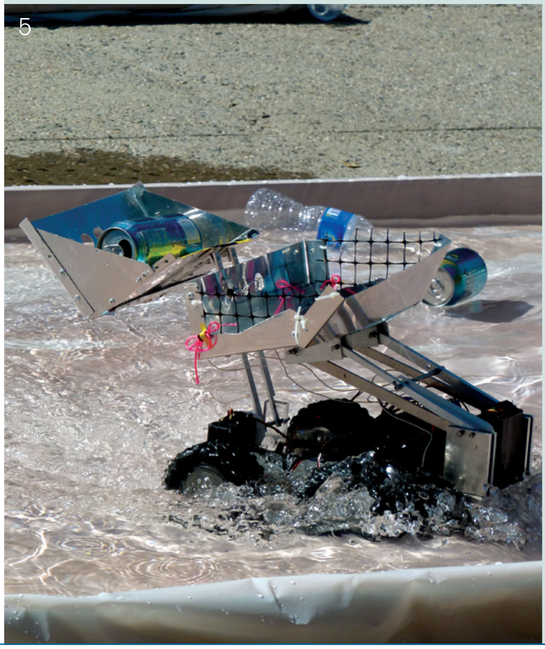

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PICTURE CREDITS
13, 15, 16, 19, 22, 25, 27, 28, 31 — Verity Smith; 14 — Roberto Osti; 17 — Materia, Inc.; 18 — Chris Snow; 20-21 — Lance Hayashida; 23 — John Takai; 27 — Shannon Boettcher; 29 — Christoph Falter; 30 — National Renewable Energy Laboratory

SPECIAL SECTION

POWER PLAYERS

Summer is almost upon us. The mercury is going through the roof, and the air-conditioning and gasoline bills are following right behind. What to do, what to do?

At Caltech, we're thinking globally and acting locally, as someone once said. This special section includes a two-page campus map, suitable for framing, that highlights our efforts to be good stewards of our own little 129 acres. In the other 16 pages, you will meet nine people whose alternative-energy research will, we hope, help change the world. Many of these faces will be familiar to regular readers of *E&S*.

Clockwise, starting from the upper left, are aeronautical engineer John Dabiri; chemist Bob Grubbs; chemical engineer Frances Arnold; chemist Harry Gray; computer scientists Steve Low and Mani Chandy; materials scientist Sossina Haile; applied physicist Harry Atwater; and, in the center, chemist Nate Lewis. —*DS*

Fishing for Wind

By Marcus Y. Woo

One day about five years ago, John Dabiri (MS '03, PhD '05) had a fishy idea. He was studying how air flows around solid structures—not unusual for an aeronautical engineer. In particular, he was trying to make wind turbines work efficiently amid the swirling gusts near buildings and skyscrapers, providing a source of renewable energy for cities. But as he played with the equations, he realized that they looked a lot like the ones that govern the flow of water through a school of swimming fish.

The arrangement of wind turbines is crucial for their efficiency, Dabiri says. Nature is often quite the engineer, and—mathematically, at least—the fluid dynamics around swimming fish are more or less optimized for efficiency. Once he saw the connection between fish schools and wind turbines, it seemed natural to put them together. Now, what began as a curiosity has become a new approach to wind power that offers a tenfold improvement over conventional wind farms.

Because wind speeds are always changing, wind turbines produce only 25 to 30 percent of their maximum potential power output. But if every currently existing wind turbine were churning out as much power as possible, the United States would have the capacity to generate some 40 billion watts of wind power, which would account for 2 percent of the nation's electricity. The maximum potential capacity of land-based wind power in the continental United States is estimated to be about 10 trillion watts, or terawatts (TW). Building wind farms on every suitable patch of land in the world could provide 75 to 100 TW. Considering that global power consumption was about 15 TW in 2008, wind could—in principle—power the entire planet.

But one big problem with wind power is that conventional turbines—the ones that resemble huge propellers—need a lot of space. If these so-called horizontal-axis wind turbines are too close together, the wake behind the spinning blades interferes with adjacent turbines. To get the most out of each turbine, they have to be about 6 to 8 blade lengths apart and 20 blade lengths downwind of each other. With blades that can be 100 meters long, these turbines quickly occupy a lot of real estate.

Wind farms supply about 2.5 watts of power for every square meter of land. (See "Sustainable Energy—Without the Hot Air," *E&S* 2010, No. 3.) If wind were to be the world's sole source of energy, those wind farms would have to occupy a combined area equivalent to more than 60 percent of the United States. That's clearly impractical, even without considering the minor difficulties: the wind doesn't blow all the time, and some places can only muster a gentle breeze at best.

Wind power is generally considered a mature technology. In theory, wind turbines can convert 60 percent of wind energy into electricity. In practice, the best are already at 50 percent. But even though we seem to be pushing the limit, Dabiri is discovering that there's still plenty of room for improvement.

Dabiri's fish-inspired wind farms use the lesser-known vertical-axis turbine, which looks a little like an eggbeater jutting out from the ground. When fish swim, they leave a horizontal row of regularly spaced vortices in their wakes; what would happen, he wondered, if he placed his downwind turbines in those vortices, and let them spin the turbines? In the spring of 2009, he assigned two grad students, Robert Whittlesey (MS '09) and Sebastian Liska (MS '09), to run a simple simulation of this arrangement as a class project. Astonishingly, they found that the turbines pumped out 10 times more energy per square meter.

"I play around with a lot of ideas, and the majority of them go to the scrap heap," Dabiri says. "But after the students came back with such compelling results, I started to get excited that this could be a viable option."

Individually, a vertical-axis turbine is less efficient than its monolithic cousin. But taken as a group, they can be positioned to squeeze as much power as possible from a given plot of land. Horizontal-axis turbines only capture the wind that blows through the circles swept by their blades, allowing precious energy to escape through the gaps between them. Vertical-axis turbines, on the other hand, can be bunched together until they're almost touching, harnessing the energy of almost all the air that blows by.

At the beginning of 2010, Dabiri used some of his faculty start-up funds—which are provided to new faculty to build their labs—to buy a two-acre plot of land on the windy plains outside Lancaster, California. Here, at the Field Laboratory for Optimized Wind Energy

Far right: John Dabiri is a professor of aeronautics and bioengineering.

Right: When a fish swims, it leaves behind vortices in its wake. By arranging vertical-axis turbines in a pattern similar to those vortices, Dabiri is designing wind farms that are up to 10 times more efficient than conventional ones.

(FLOWE), an array of half a dozen turbines has proven that Whittlesey's and Liska's results were right—and since then, the researchers have even improved on the fish-school models. "When we say we can increase the power output by an order of magnitude," Dabiri says, "it's not just a theoretical prediction."

The key is that every turbine rotates in the opposite direction from its nearest neighbors. "That's the secret sauce," Whittlesey says. No one's exactly sure why, but it may be that the opposing spins lower the local drag on each turbine, allowing it to whirl faster and generate more power.

Vertical-axis turbines have other advantages. They're safer for birds. And instead of being 100-meter-tall structures that would send Don Quixote into a tizzy, vertical-axis turbines are around 10 meters tall. Because they're quieter and smaller, they can be distributed more widely and can be built closer to population centers. In fact, Dabiri is already working with the Los Angeles Unified School District to construct turbines at a new high school in San Pedro in 2012.

Other Caltech faculty members have gotten in on the action. Chemist Robert Grubbs is developing new materials to build stronger, lighter, and cheaper turbines (see page 16), and, by manipulating structures at the nanoscale, Julia Greer is creating other materials for more durable blades. Aeronautical engineers Beverley McKeon and Mory Gharib (PhD '83) are fine-tuning turbines to control the airflow for maximum efficiency. And mechanical engineer Tim Colonius is running complex computer models of turbine wakes.

Meanwhile, the field tests continue. In one set of experiments, postdoc Matthias Kinzel is throwing fake snow into the whirling turbines. By taking pictures and video of the swirling flakes, he can measure exactly how the air flows and compare the physics with conventional turbines.

Even if Dabiri's arrangements aren't yet optimized, they're still a vast improvement over the status quo—and more than good enough for commercial use. This summer, he's building a few dozen more turbines at the test site, bumping the total to 42. "These experiments will, for me, be the conclusive evidence that this approach works," Dabiri says. And there's nothing fishy about that.

Dabiri's wind-energy research is supported by grants from the Gordon and Betty Moore Foundation and from the National Science Foundation's Energy for Sustainability program.

For more information, see http://bioinspired.caltech.edu.

Creative Chemistry

By Kathy Svitil

Often, the Nobel Prize rewards work that seems esoteric or even impenetrable to the Average Joe and Jane. It's probably not obvious how palladium-catalyzed cross-coupling reactions (which received the 2010 Nobel Prize in Chemistry) or spontaneous symmetry breaking in subatomic physics (one-half of the 2008 Nobel in Physics) fit into a regular workaday life.

At first blush, the olefin metathesis catalytic reactions for which Robert Grubbs shared the chemistry Nobel in 2005 seem just as confounding. "Olefin metathesis" isn't exactly cocktail party chatter. But what Grubbs's catalysts have made possible is definitely something to talk about: countless new types of environmentally friendly plastics, lubricants, biofuels, herbicides, pharmaceuticals, and more.

An "olefin" is a hydrocarbon with at least one carbon-to-carbon double or triple bond, and "metathesis," from the Greek word for transposition, is a chemical change of partners. (See "The Metathesis Waltz," *E&S* 2005, No. 4.) In the reaction, two carbon atoms (let's call them Fred and Ginger) connected by a double (or sometimes triple) bond hook up with two other carbon atoms (say, Ken and Barbie) also connected by a multiple bond. When the dance ends, Ken has embraced Ginger and Fred has gone off with Barbie. But since whatever accessories each dancer was wearing (in the form of chemical side chains) stay with their original carbon atom, the result is new chemical compounds with different properties. In nature, unassisted by chemists, these sorts of transformations just aren't possible; Bob Grubbs created chemical catalysts that don't just make them happen, but make them happen quickly, efficiently, and *greenly*.

Green because, compared to many other chemical reactions used in industry, Grubbs's catalysts

can chug along in water instead of having to be bathed in toxic solvents like benzene. The reactions require fewer reagents, which are the other chemicals needed to make the process work, and churn out higher quantities of the desired end-products—often without any annoying *by*-products.

One focus of the Pasadena-based company named Materia, which Grubbs cofounded in 1998 to manufacture and sell the catalysts, is creating tougher, lighter materials to be used for the gracefully swooping blades of wind turbines. Wind energy presented a good commercial opportunity, Grubbs says, because it's a rapidly growing field and the qualification process for new composites for turbine blades is far shorter than that for, say, airplane wings. The venture now has the interest of several major turbine producers worldwide.

These turbine blades and other parts used to be made of metal; by using fiber-reinforced composites, new designs can be tested quickly until just the right combination of aerodynamic shape, strength, and lightness is found. The process begins with an inexpensive substance called dicyclopentadiene, which is a small molecule created as a by-product of oil refining. These molecules are called monomers—the building blocks from which a polymer is made. The blades are formed from glass- and carbon-fiber mats pressed into a mold and then filled with a mixture of the monomer, the catalyst, and other ingredients. The catalyst links the monomers together into a solid polymer and, depending on what else was mixed in, the resulting materials will have a variety of different properties; more of one additive might make the blades lighter, while more of a different one might add stiffness.

Materia is helping to develop turbine blades up to 70 meters long—nearly 15 meters longer than the biggest ones out there now—for use on gigantic offshore platforms. "To get to those sizes, you need a newer generation of materials that are lighter and tougher," Grubbs says.

Closer to home, Materia is crafting blades for John Dabiri's vertical-axis wind turbines (see page 14). Meanwhile, Materia and the agribusiness conglomerate Cargill have joined forces in a start-up, Elevance, that is turning things like chicken fat and soybean oil into a host of environmentally friendly versions of consumer goods normally based on petroleum products. In addition to biodiesel and jet fuel, Elevance's smorgasbord of merchandise includes soaps, vegetable- and soy-wax candles, and ingredients used in lipsticks and skin-care products.

Grubbs continues to be surprised at the diversity of applications for his chemical progeny. "When we developed the first catalyst, we had no idea what it would be good for," he says. (See "Polymer's Progress," *E&S* 1988, No. 4.) "We're just trying to make better catalysts and understand their reactions. Every new catalyst opens up new opportunities, and then someone stumbles upon the uses." E&S

"We're just trying to make better catalysts and understand their reactions. Every new catalyst opens up new opportunities, and then someone stumbles upon the uses."

The wind-energy-technology work is funded by the Gordon and Betty Moore Foundation and the National Science Foundation.

Left: Robert Grubbs is the Victor and Elizabeth Atkins Professor of Chemistry.

Above: A prototype mold for a section of a wind-turbine blade at Materia's R&D facility.

New Power Plants

By Marcus Y. Woo

Frances Arnold joined the bioengineering revolution at just the right time. The 1970s saw the first genetic-engineering experiments, in which scientists learned to manipulate proteins, cells, and simple organisms at the DNA level. When Arnold finished her PhD in chemical engineering in 1985, protein engineering was in its infancy. Researchers were modifying proteins from the bottom up, tweaking the DNA code in an effort to make the protein do something new. But that's not easy, Arnold says, given that even today, nobody understands the incredible complexity of proteins well enough to predict useful mutations. Instead, she had her own idea.

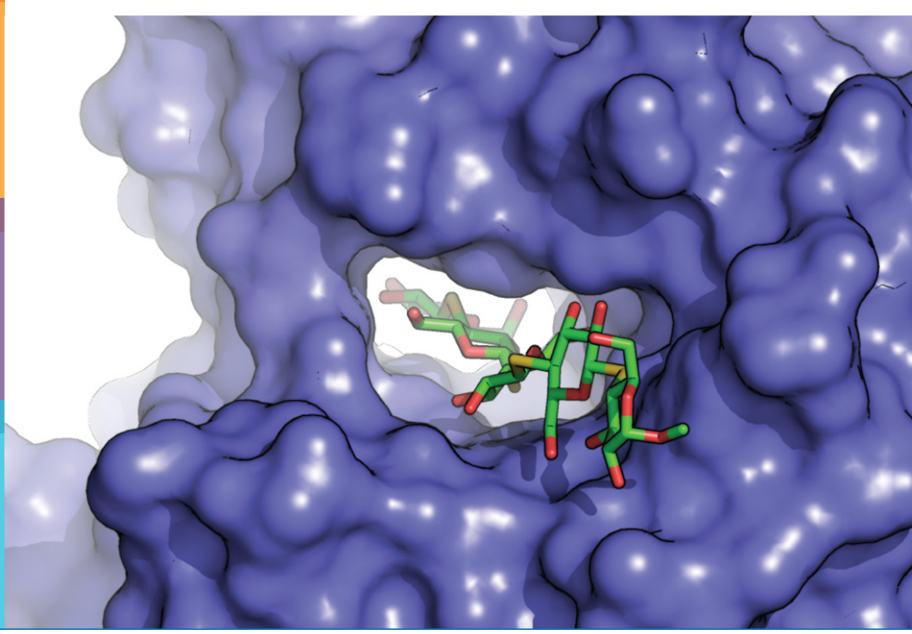
"It was obvious to me that one should use a tried-and-true process," she says. "And that's evolution." Nearly four billion years of random mutations and natural selection has led to the diverse and marvelously functional biological machinery that constitutes the life we know today, she says. Mother Nature has been the best bioengineer in history—why not harness the evolutionary process to design proteins?

Some researchers were less than enthusiastic. "People said this wasn't science, that gentlemen don't make random mutations," Arnold says. "But I'm an engineer—and a woman—so I ignored the critics."

She set off to help invent directed evolution, a technique in which you start with thousands of randomly mutated proteins, pick out those that possess a desired trait, and then breed those mutants over several generations. Her methods are now used to make products in everything from agriculture to toxicology. In the last decade, Arnold has turned directed evolution to developing better biofuels.

Biofuels, which are derived from plants, can be helpful in reducing greenhouse gases. While burning fossil fuels, such as coal or oil, pumps carbon from the ground into the atmosphere, the plants that are grown to produce biofuels absorb the carbon that burning the fuels releases.

The main biofuel in the United States is ethanol made by fermenting corn. But the process is inefficient, requiring a lot of land, energy, water, and fertilizer. Turning food crops into fuels may also cause food prices to increase. And corn-based ethanol only reduces greenhouse-gas emissions by a relatively modest amount over gasoline.



The ultimate goal is to use plant waste or dedicated energy crops—plants like switchgrass that grow easily and quickly. Biofuels from these sources generate significantly less greenhouse gases than gasoline. But breaking down cellulose—the tough molecular chain that forms a plant's cell walls—into sugars that can be fermented is complicated and costly.

Arnold and her colleagues are using directed evolution to engineer enzymes—proteins that facilitate chemical reactions—that *can* break down cellulose into glucose cheaply (see "The Race for New Biofuels," *E&S* 2008, No. 2). They've also made new enzymes for biochemical "pathways" that convert sugars into isobutanol, a more versatile chemical that in turn can be converted to aviation fuel, diesel, and plastics. And, with four carbon atoms to ethanol's two, isobutanol is a more energetic fuel.

Isobutanol was first made by James Liao's group at UCLA, which cobbled together existing enzymes from various yeasts and bacteria to catalyze the various steps along the pathway. Those enzymes were stuck into a host microorganism, which Arnold's laboratory is fine-tuning with directed evolution. "We use evolution to edit the whole thing and make it beautiful," Arnold says. The cellulase enzymes and isobutanol pathway will someday be packaged neatly inside a single organism—a superbug that turns plants to fuel.

In 2005, along with Peter Meinhold (PhD '05) and former postdoc Matthew Peters, Arnold cofounded a company called Gevo, which just went public in February. Gevo is now retooling old ethanol facilities to make isobutanol. The company has a facility in Minnesota that will churn out 18 million gallons of isobutanol per year starting in 2012. Gevo's process will use corn-based sugars to start, but will eventually switch to plant waste and other cellulosic materials.

Meanwhile, Arnold's research remains focused on more fundamental problems, such as streamlining directed-evolution techniques and seeing what other useful biological catalysts can be made.

In particular, Arnold's lab is looking for more efficient ways to make mutations. Instead of swapping out individual letters of DNA, which can prevent the protein from folding properly and thus deactivate it when too many changes are made at once, the researchers are trying recombination, also known as "molecular sex." In this method, the researchers join sequences of DNA strands from different parent organisms into one strand. Recombination generates many mutations simultaneously, yet each sequence has the basic information needed to preserve the original protein's ability to fold and function—albeit in different combinations. But there's a caveat: because the basic information in the offspring is already in the parent DNA, it's not yet clear how different—or how useful—the progeny proteins will be. The researchers, however, are trying to find out.

Recently, Arnold—along with former postdoc Pete Heinzelman, who's now at the University of Oklahoma, and graduate students Russell Komor and Indira Wu—created cellulose-digesting enzymes, or cellulases, that work at a toasty 70°C to 80°C, compared to a tepid 40°C to 50°C for regular enzymes. These high-temperature enzymes last longer and break down cellulose a lot faster. "They're better suited for industrial processes," Arnold says.

Right now, biofuels account for only about 3 percent of the nation's energy usage. But if the country maximized their potential by planting fields of dedicated fuel crops—without disrupting the food supply—biofuels could replace more than half of the nation's oil imports. So we won't be able to turn to plants exclusively, but they could take a big chunk out of our reliance on oil—especially imported oil, which, Arnold points out, constitutes a national-security risk.

"We need to get rid of that addiction to Middle East oil," she says. "It's an expensive and unreliable source of critical liquid fuel and chemicals." The current unrest in that volatile region has pushed oil prices above $100 a barrel, the highest levels since the 2008 financial crisis. And, of course, there's the issue of climate change.

But revolutionary science and technology notwithstanding, nothing can replace a little prudence. "In the end we have to use less," Arnold says. "There's not enough biomass to feed everyone's desire for cheap fuel. Oil is a precious resource that we must stop wasting." E&S

Arnold's research is funded by the U.S. Army, the Department of Energy, the National Science Foundation, DARPA, and the Caltech Innovation Institute.

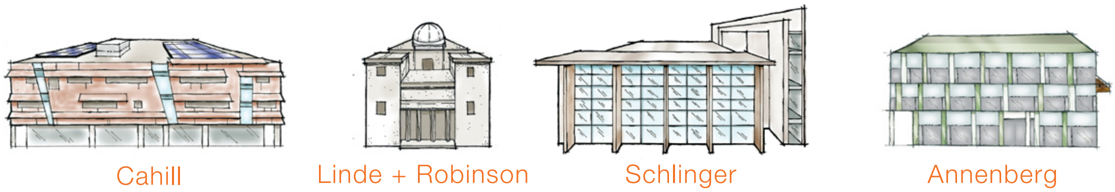
Right: Frances Arnold is the Dickinson Professor of Chemical Engineering, Bioengineering, and Biochemistry.

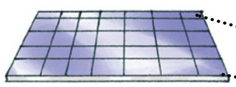
Left: A cellulose polymer (green) threads its way through an enzyme called cellobiohydrolase II (blue), which breaks it down.

Greening Caltech

LEED Buildings

Three Caltech building
Besides using daylight
energy-efficient fume h
voltaic array; and Anne
+ Robinson, slated to
status, will reuse rainw





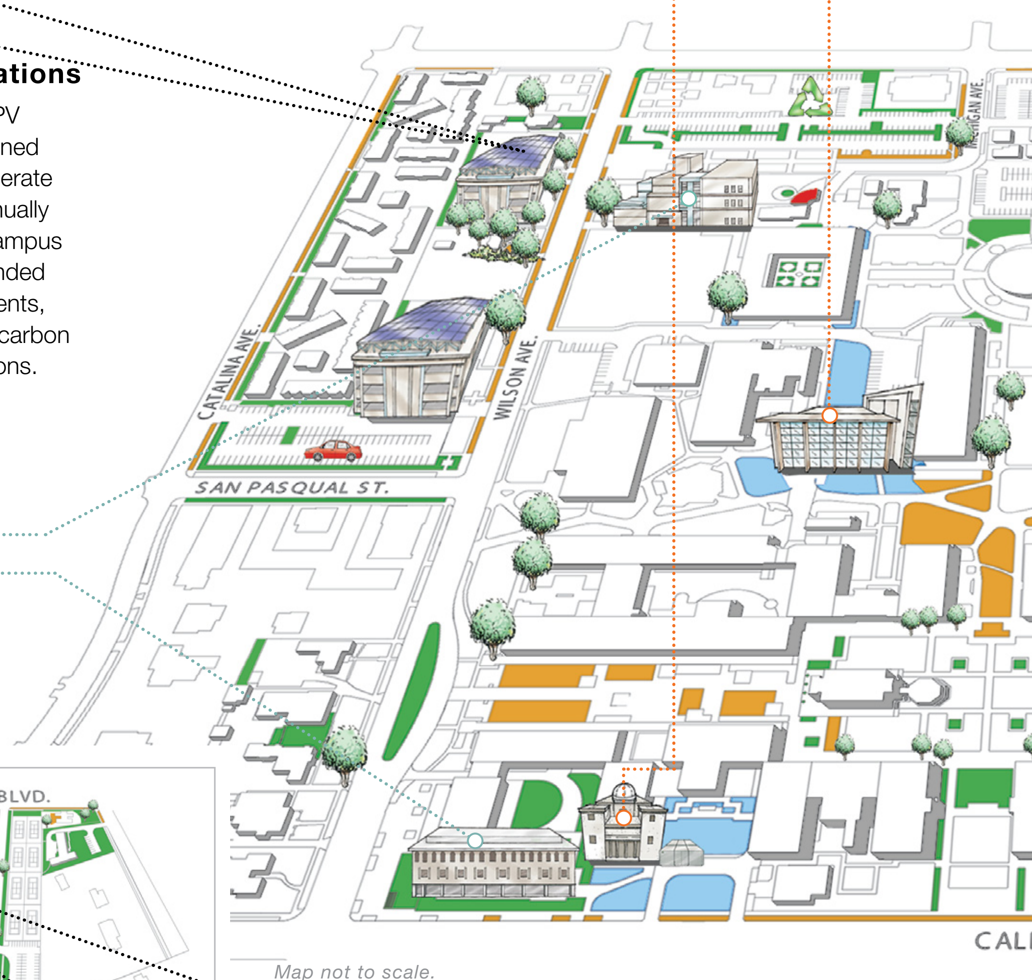
Photovoltaic Installations

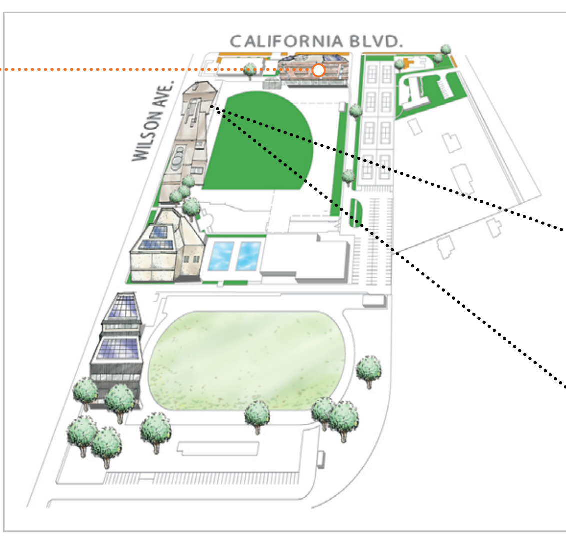
Eight separate buildings fly PV arrays that produce a combined capacity of 1.3 MW and generate 1,925 MWh of electricity annually (roughly 2 percent of total campus load). These installations, funded by power-purchase agreements, reduce the Institute's yearly carbon emissions by 1,600 metric tons.

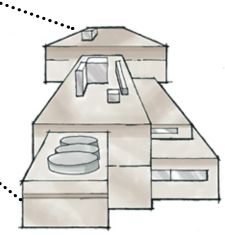
Energy Efficiency

Broad
South Mudd

Extensive upgrades have saved more than 8 million kWh and $1.3 million in the last two years.







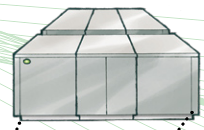
Cogeneration Plant

This on-site, 12.5-MW natural-gas power plant cogenerates heat and steam to meet approximately 60 percent of the total campus energy load. In 2004 (the year of installation), the plant won an EPA Energy Star award.

TURF REDUCTION: Possible turf replacement (583,000 sq. ft.)

IRRIGATION SYSTEMS: Existing high efficiency / drip systems (38,000 sq.ft.)

gs have been certified LEED Gold by the U.S. Green Building Council. : to illuminate 75 to 90 percent of all occupied spaces, Schlinger features hoods with auto-closing sashes; Cahill supports a 40-kW solar photo- enberg's chilled beams lessen the need for air conditioning. And Linde become the first renovated lab in the country to achieve LEED Platinum vater as well as sunlight.

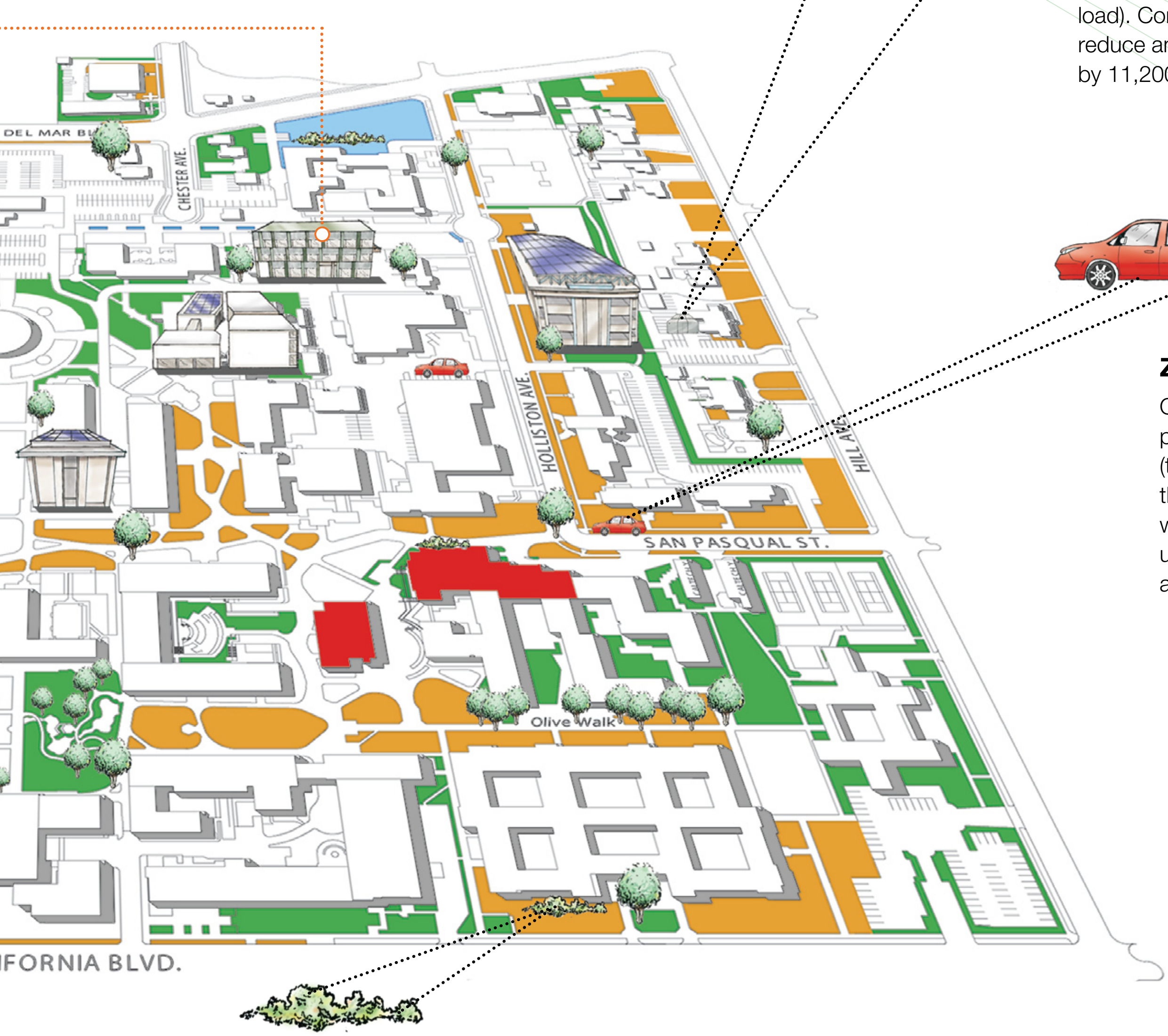


Fuel Cells

Installed with capital from the Bloom Electrons Service, Caltech's 20 units offer 2 MW of total capacity, providing 17,000 MWh of electricity annually (roughly 15 percent of campus load). Combined, these units reduce annual carbon emissions by 11,200 metric tons.

Zipcars & Hybrids

Caltech's car-sharing program offers four cars (two of them hybrids) to the campus community, while the Institute's fleet utilizes 125 electric carts and four hybrid vehicles.



Gardens

These xeriscaped open spaces feature native and climate-adapted plant species that require less water while mitigating the urban heat-island effect. All landscaped areas are now watered by a computerized irrigation system that detects and adapts to real-time climate conditions.

Campuswide Recycling

Caltech's recycling program diverts approximately 40 percent of the Institute's waste (roughly 1,000 tons) from landfills each year. Nonrecyclable materials are sent to a waste-to-energy facility in Long Beach, while hazardous and electronic waste is recycled or safely disposed of locally by licensed third-party vendors.

RAIN GARDENS:
Vegetation lets rain soak in (850,000 sq. ft.)

FOOD COMPOSTING:
Chander Dining Hall, Red Door Café, Broad Café

Going All In

By Katie Neith

Chemist Nate Lewis (BS, MS ’77) is trying to beat nature at its own game, and the federal government has placed a $122 million bet that he and his team can make it happen. By replicating photosynthesis in manmade devices, he hopes to produce fuel from the sun at a rate that is 10 times more efficient than in typical crops and at a price that makes it affordable.

“We’re smarter than a leaf—they have no brains!” exclaims Lewis. “We can figure this out.”

As director of the Joint Center for Artificial Photosynthesis (JCAP), a new research hub funded by the U.S. Department of Energy (DOE), Lewis is charged with harnessing both the expertise of nearly 200 scientists and the energy of the sun to turn carbon dioxide and water into storable fuel.

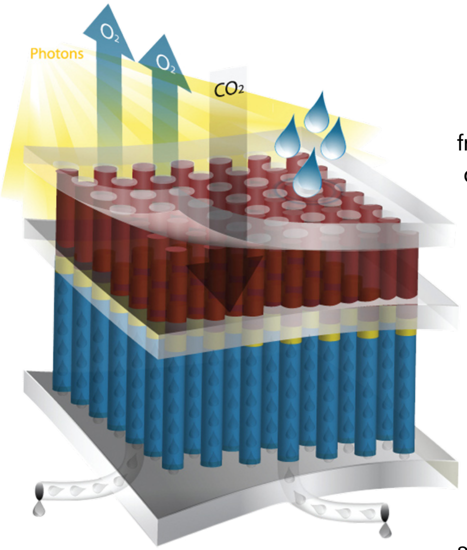
The project, which Caltech leads in partnership with the DOE’s Lawrence Berkeley National Laboratory (LBL), will be housed in Jorgensen Lab, a former computer science building on the Caltech campus. However, only about 90 of JCAP’s scientists will be housed there. The rest, at LBL and elsewhere, will be connected via telepresence—the latest, most technically advanced video-conferencing technology—so that the entire organization will operate under one virtual roof.

“JCAP’s goal is to try to take what has made some progress in labs around the world, and to do in five years what would otherwise have taken maybe 55 as we waited for the individual pieces to come together. It’s a bold experiment in innovation,” Lewis asserts.

As Lewis points out, the problem is complex. Researchers know how to make electricity from the sun and how to make it efficiently with conventional solar panels, but they cost a lot of money. They also know how to make solar fuel efficiently, but it’s not cheap—more-affordable solar panels would have to cover 10 rooftops just to power one home, says Lewis. In addition, the technology needs to be durable. For example, real leaves are cheap, but their photosynthetic complexes only last for about 30 minutes before breaking down.

“A successful commercial product has to be cheap, efficient, and long-lasting,” explains Lewis. “Currently, we can give you two of those, but not all three at the same time. The goal of JCAP is to get all three.”

So JCAP is upping the stakes of the solar-fuel game and going all in. Lewis says that researchers at Caltech have drawn many of the cards needed. We have light-absorbing nanowires to capture energy from the sun (see page 26). We also have



catalysts that can react with water to make hydrogen fuel (see page 24). However, we don't yet hold a winning hand—an integrated system that does everything at one time and under a single set of conditions.

"Our goal is not simply making another generation of an existing technology, or lowering the cost of doing what we already know how to do. We're aiming to develop a totally new function and that's why the prize is so great," he says.

Lewis and his team plan to accelerate the rate of discovery of cheap, durable, readily available metal oxides to see which ones can capture and convert the energy of sunlight into chemical fuels at moderate temperatures and remain functional for extended periods of time. His game plan borrows from the divide-and-conquer approach developed for the Human Genome Project, in which robotic DNA sequencers each worked on reading their own little bit of the genetic code. "We claim we're going to make, screen, and measure a million compounds every single day," says Lewis. "We're going set up a team of people with automation and robotics so that any good idea—and all its variants—can be pursued automatically, that very same day."

Other JCAP members will attack the problems inherent in melding nanoscale components into fully functional macroscale devices. These devices will then be built into ever-larger systems until a practical real-world scale is achieved.

"Individual research groups couldn't possibly do what we are trying to do," says Lewis. "Only a hub can work on all the technology gaps all at once, and, at the same time, draw on a national laboratory and on the academic infrastructure that a major research university can provide." He compares the work to another, slightly smaller team that also took a concept from nature and applied it to technology. "We're the Wright Brothers," he says. "They figured out how to make something fly like a bird, but without feathers. We're making a 'leaf,' but it won't look like a leaf."

In fact, he says his artificial leaf is more likely to look like bubble wrap and will be designed to function like a multilayer, high-performance fabric. It will absorb sunlight, CO_2, and water vapor, allowing oxygen to escape. Molecules in the inner layer will catalyze the reactions that produce the fuel, which will be wicked out by the bottom layer—the way microfiber athletic wear wicks sweat from the body. He predicts that the first fully functional prototype will be available in a few years.

"The only way to get off the ground on the sixth try is to build the first five prototypes, learn from your mistakes, and be bold enough to say 'We are willing to fail' again, if that's what it takes," says Lewis. He points out that if we can find a way to make fuel from the sun, then it doesn't matter what specific molecule it is we make; we can turn one fuel into another. "It just matters that we make *a* fuel from the biggest energy source we have," he says. "We would think about our energy problem so differently if we can get this card on the table." E&S

"JCAP's goal is to try to do in five years what would otherwise have taken maybe 55."

Besides Caltech and LBL, JCAP partners include the SLAC National Accelerator Laboratory, UC Berkeley, UC Santa Barbara, UC Irvine, and UC San Diego.

Other Caltech members of the leadership team include: Bruce Brunschwig, member of the Beckman Institute and director of the Molecular Materials Resource Center; Harry Atwater; Harry Gray; Jonas Peters, the Bren Professor of Chemistry; and Michael Hoffman, the Irvine Professor of Environmental Science.

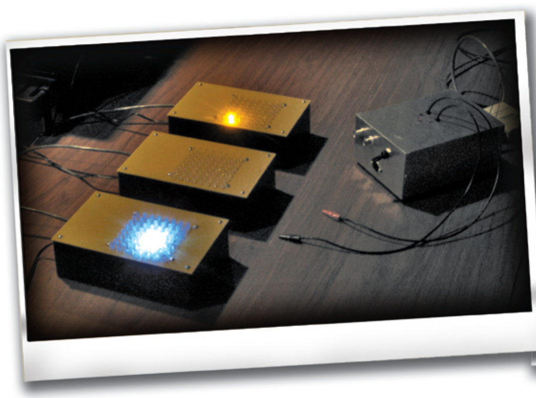
More information on JCAP can be found at http://solarfuelshub.org.

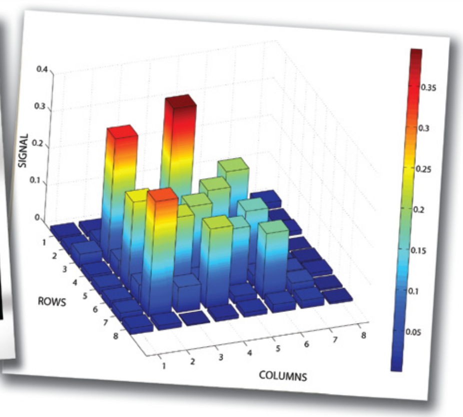
Left: Nathan S. Lewis is the Argyros Professor and professor of chemistry.

Above: In an "artificial leaf" prototype, the upper half absorbs light, CO_2, and water and allows oxygen to escape. Customized molecules embedded in an inner layer catalyze the reactions that produce the desired fuel, which is wicked away by the base layer.

The Sunshine General

By Lori Oliwenstein





Harry Gray, a five-star general in the Solar Army, is very busy. Busy recruiting the hundreds of student volunteers needed to comb through the periodic table, looking for just the right metal-oxide mixtures to help turn sunlight and water into hydrogen fuel. Busy trying to find just the right way to determine which of these catalysts will be the munition of choice. Busy integrating the chosen catalysts into solar weapons that will work under battlefield conditions—out in the open, exposed to the elements.

In short, Harry Gray is busy trying to power the planet. Naturally.

But he can't do it alone. Which is why, on the door of his office in Caltech's Beckman Institute—of which Gray is the founding director—is taped a recruiting poster. Gray's broadly grinning face has replaced Uncle Sam's sterner visage, but that well-known finger points out with just as much urgency. "I WANT YOU," the poster reads, "FOR SOLAR ARMY."

Should you heed this call, your task would be nothing less than helping Gray and his Center for Chemical Innovation (CCI Solar) colleagues in their quest to mimic photosynthesis in the laboratory, creating a storable fuel from sunlight.

The emphasis, Gray notes, is on *storable*: Solar cells convert sunlight into electricity, but when the sun goes down, the power goes off. Fuel cells similarly convert hydrogen, methanol, or some other chemical into electricity. A solar-driven fuel cell would split water by day, producing hydrogen that could be squirreled away. At night, it would act as a standard fuel cell, producing water and electricity.

First, however, we need that elusive catalyst. "Nature's version is the oxygen-evolving complex of Photosystem II," says Gray. "That's the catalyst that makes oxygen from water here on Earth." But recreating the oxygen-evolving complex in a nonliving fuel cell is impossible; too many moving parts. And so the hunt is on for a simplified version, a combo of metal oxides that can do the trick with something close to the skill of nature itself.

You might think the easiest way to go would be to find a single, powerful water-splitting metal oxide—and you'd be right, but naive. "The ones that are really great are so rare that we can't scale them up worldwide," says Gray. "And the ones that are abundant just don't work well enough."

Which is why the Solar Army is focusing its search on the parts of the periodic table where the cheap, plentiful stuff lives—sodium and iron and titanium and their ilk—but looking at them in oxidized, mix-and-match amalgamations. After all, the wider a variety of metal oxides you can cram into a single catalyst, the broader the spectrum of sunlight you'll be able to gather, since each material will have certain colors of light with which it is best able to interact.

This makes the Solar Army's reconnaissance mission—to find the best mixture of three, four, maybe even five metal oxides—rather daunting: "There are millions of possible combinations of just two to three metals," says Gray. "If you're looking at combinations of four to five, you're talking about billions."

Gray's army has mustered brigades at more than a dozen other universities, including the University of Wyoming, Penn State, and Texas A&M, and corporations like Dow and 3M. Most recently, Gray says, the U.S. Navy has asked to hear more about the project. "The Navy has a lot of interest in our army," Gray laughs.

But the real foot soldiers in this war against energy inefficiency are the more than 400 high-school and college student-volunteers across the United States and in Germany. They are the ones who—armed with the Solar Army's best weapon to date, the Solar Hydrogen Activity Research

Right: Harry Gray is the Beckman Professor of Chemistry and founding director of the Beckman Institute.

Above left: These LED pulsers, built at Caltech, can quickly scan a glass plate of metal oxides to find the ones that make the most electricity.

Above right: In this instance, the tallest bars are the samples containing iron oxide.

Kit (SHArK)—are testing metal-oxide combinations that they prepare in their classrooms and laboratories.

It's a work in progress. Previous versions of the kit used an inkjet printer to deposit metal salts on a glass plate, which was then scanned by a LEGO Mindstorms gadget that included a laser pointer. (See "The Solar Army is Recruiting," *E&S* 2010, No. 1.) "It was this method that found our first big hit—zinc-yttrium-iron," says Gray.

Recently, however, Gray's colleagues Jay Winkler (PhD '84) and Bruce Brunschwig have developed the next generation of SHArKs, in which the LEGOs and lasers have been replaced by legions of LEDs. "The advantage of our new screening system is speed," Winkler explains. "The laser-scanning system would take four to six hours to scan a single sample plate. The LED scanners can scan a plate in one to two minutes."

The system is not only fast, but effective: To date, says Gray, the SHArKs have identified a half-dozen "really good-looking" catalysts, though the search is by no means over. "We want to find as many as we can," he says, "because the solar fuel cell isn't finished yet, and we won't know if the catalysts we find are compatible with the fuel cell until then."

And so, while the younger members of the army march toward a better catalyst, Gray and Nate Lewis (see page 22) are working to perfect that fuel cell.

In particular, Gray's group is looking for the best material for the cell's anode, where sunlight is absorbed and its energy funneled to the surface, which will be coated with the Solar Army's water-splitting catalyst. "The big challenge for the anode," says Gray, "is to get a stable material that can absorb as much light as possible."

Tungsten oxide is the best bet at the moment, but it needs a little extra help to reduce its band gap—the range of the solar spectrum it can't absorb. Enter postdoc Qixi Mi, who has doped the tungsten oxide with nitrogen and dropped the band gap from 2.6 to 1.8 electron volts (eV)—creeping ever closer to the team's ultimate goal of no more than 1.7 eV.

"It's a very promising material," says Gray. "Now, hopefully, the Solar Army will come up with a great catalyst to put on Qixi's great tungsten-oxide anode. That would be a very big win."

It's coming, Gray insists. But it's not time to stand down the troops quite yet. "The Solar Army still has a lot of work to do," he says. "And they're doing it." E&S

CCI Solar is a program of the National Science Foundation. Other parts of the program have been funded by Stanford's Global Climate and Energy Project, BP, Chevron Phillips, the Arnold and Mabel Beckman Foundation, and the Gordon and Betty Moore Foundation.

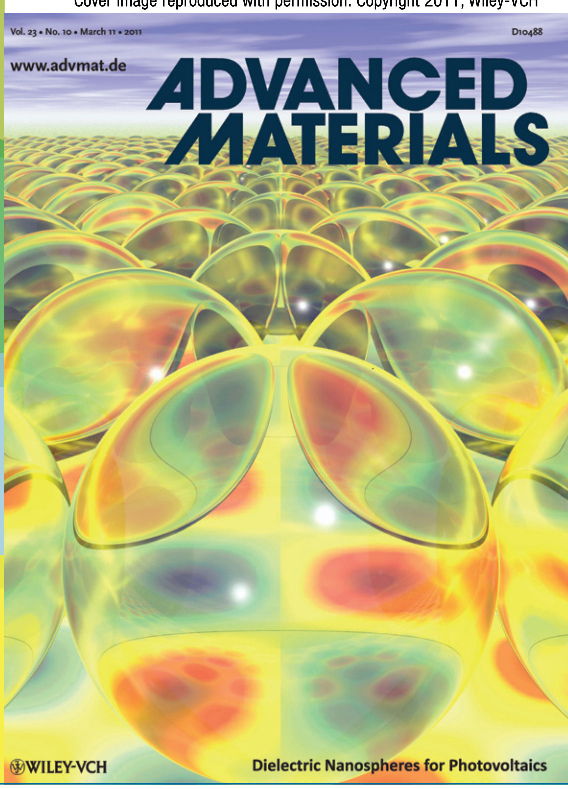
To learn more about CCI Solar, visit: http://www.ccisolar.caltech.edu/index.php.

Solar Sculptures

By Lori Oliwenstein

Harry Atwater's solar cells look like no other you've seen before. They're spiky, hairy, bendable. They resemble uninflated mylar balloons. Or they're covered in tiny glass beads, looking more like microscopic Martian colonies than devices meant to convert sunlight into energy.

These solar cells are also well on their way to being better than any other. One of them—a gallium-arsenide thin-film cell produced by Alta Devices, a Caltech startup cofounded by Atwater—recently converted a previously unheard-of 27.6 percent of the light aimed at it into electricity. Such record-breaking efficiencies, Atwater says, come from "sculpting and molding the flow of light through materials" to wring as much energy from it as possible.



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And one of the ways to do that is to trap the light, keep it contained. After all, the longer you can hold onto light, the more likely you are to absorb its energy. "We concentrate light the way a lens does, but in thin, flat films," Atwater says.

Emphasis on *thin*. Thin is most definitely in, says Atwater, because thin solar cells use less material, making them less expensive to produce, and because they can bend without breaking. You can even roll them up like bolts of fabric, which opens up a world of possibilities. Solar clothing, anyone?

Atwater's group has already made centimeter-sized thin films capable of absorbing up to 96 percent of a single wavelength of sunlight or 85 percent of the total sunlight collectible up on your roof. These films are actually arrays of silicon nanowires, each about a hundred millionth of a meter long, all reaching for the sun like stalks of corn.

Today, the team is growing "cornfields" hundreds of square centimeters in size. And "growing" is the operative word—the wires are cultivated by deposition on a crystalline template and harvested by pouring a polymer over the entire array. Peeling this thin film off exposes the bare earth, as it were, ready for another crop. Now being developed by a start-up called Caelux—founded by Atwater, Nate Lewis (see page 22), Michael Kelzenberg (MS '06, PhD '10), and Morgan Putnam (MS '08, PhD '10)—the arrays keep getting better and better. "We've made cells that are 8 percent efficient, and we have good reason to believe we will double that," says Atwater.

Meanwhile, Atwater—uninterested in resting on his wiry laurels—is pursuing even more unusual ways of milking sunlight for every watt it's worth.

The latest, developed by postdoc Jonathan Grandidier, grad student Dennis Callahan, postdoc Jeremy Munday, and Atwater, arranges tiny glass beads on a thin layer of amorphous silicon. When light shines on the beads, it becomes trapped inside and begins circulating around and around; and with each circuit, a bit of it leaks into the silicon below. This trapping method is called a "whispering gallery," because it's based on the same wave-focusing physics that allow a whispered remark on one side of the domed Statuary Hall in the U.S. Capitol to be heard clear across the rotunda.

In their quest to devise the hardest-working solar cells around, Atwater and his crew have found themselves questioning longstanding theoretical assumptions. "We're challenging what we thought were hard-and-fast efficiency limits on how much light can be absorbed by a material," Atwater says. "We know now that we can significantly exceed those limits. It turns out that, at submicron and nanometer scales, the rules are fundamentally different. It's a very different way of thinking."

That's not the only place where Atwater is thinking differently. "It will take an 800-gigawatt generating capacity to meet U.S. energy needs, which will require tens of thousands of square miles of solar cells," Atwater notes. "We make concrete on that scale, but sand and gravel are abundant. On the other hand, many of the best materials for thin-film solar cells—tellurium, for instance—come from rare ores."

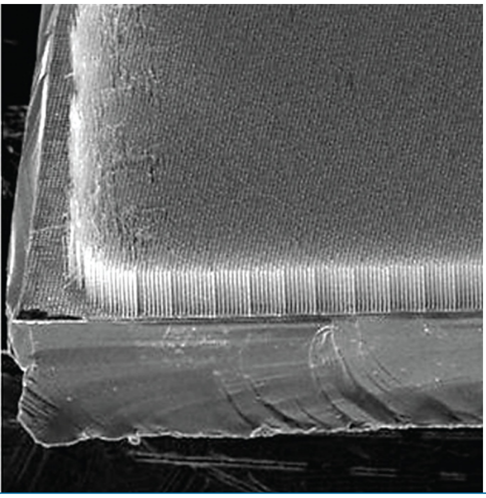
Which is why Atwater, along with Lewis, is looking to Earth-abundant materials. Many previously overlooked materials may well have solar potential, says Atwater—but only if we put in the time and effort to figure out how to exploit them.

"Zinc phosphide, copper oxide, or zinc sulfide could rival the efficiencies of the most expensive and rare materials," says Atwater. "But we haven't done the basic chemistry and physics necessary to develop them properly. We need to bring our understanding of these Earth-abundant materials up to that of our best solar materials, like gallium arsenide."

In addition, Atwater's team is searching for materials to pair up with the already well-studied elements like silicon. "If we could make tandems of solar cells with different light-absorbing properties and different band gaps—combine silicon with, say, copper oxide—we would end up with cells that are much more efficient," Atwater says.

Such down-in-the-trenches efforts are aimed at expanding "the materials genome"—creating a portfolio of new materials from Earth-abundant building blocks, and measuring their fundamental properties. The team will be making new materials, then making them better and trying to understand them more completely. These are, says Atwater, the efforts that will make the difference in the end; the efforts that will help us harness the sun.

"Beyond the basics, there are also a lot of little details that transcend fundamental discovery; they're what I call cycles of learning," he says. "That's where the science meets real engineering. And that's what makes this work so satisfying." e&s



Much of the solar-cell research is done by the "Light-Material Interactions in Energy Conversion" Energy Frontier Research Center, funded by the Department of Energy. The silicon-wire research is funded by BP, and the work on Earth-abundant materials is funded by the Dow Chemical Company.

Above: Harry Atwater is Hughes Professor and professor of applied physics and materials science, and director of Caltech's Resnick Institute.

Far left: Atwater's solar cells based on glass nanospheres were described in the March 11, 2011, issue of *Advanced Materials*.

Left: Silicon-wire solar arrays use just one-fiftieth the silicon of a conventional solar cell but still absorb 85 percent of total sunlight.

Focus on Chemical Fuels

By Katie Neith

In the spring of 2008, Sossina Haile participated in a National Research Council study on renewable electricity that discussed solar energy and how to store it. "It struck me that as a nation, and as a planet, we weren't making much progress," she says. "There was a lot of talk about the sun being our leading resource, but the majority of approaches to take advantage of it were not working." She returned to her lab armed with a list of failed ideas and the determination to cook up a new recipe for turning sunlight into fuel using ingredients from research she was already doing.

"I decided that maybe we could take advantage of our knowledge of fuel-cell materials to forge a different path," says Haile. A fuel cell is a "clean" technology that converts chemical energy to electricity. Basically, this amounts to a chemical reaction in which a fuel, let's say hydrogen, is split into electrons and protons. The electrons generate an electrical current through a wire, while the protons pass through a conductive medium called an electrolyte. They meet back up in the cathode, where they react with oxygen to form water vapor.

We usually think of electrolytes in terms of sports drinks, but Haile's electrolytes are solids; in fact, some are ceramics. One of them—cerium oxide, or ceria for short—looked like it might be the key ingredient for turning concentrated solar heat into fuel. Cerium oxide is commonly used in catalytic converters and self-cleaning ovens—both of which use heat to break down unused chemical-fuel molecules, be they unreacted hydrocarbons or rib-roast grease. And cerium is nearly as abundant as copper, an important consideration for a technology intended to be adopted globally. (See "Put Some Sunlight in Your Tank," *E&S* 2009, No. 2.)

"From working on fuel cells, we knew

Left: Sossina Haile is a professor of materials science and chemical engineering.

Above right: Concentrated sunlight enters the solar reactor, striking the ceria (green). The reacting gases (blue arrows) enter from the sides and flow through the porous ceria, and the fuel gases (red arrow) exit out the bottom.

that ceria had the ability to uptake and release oxygen, good catalytic properties, and great thermal stability," says Haile. "It appeared to have exactly the characteristics you'd like in a thermochemical catalyst, so we gave it a try."

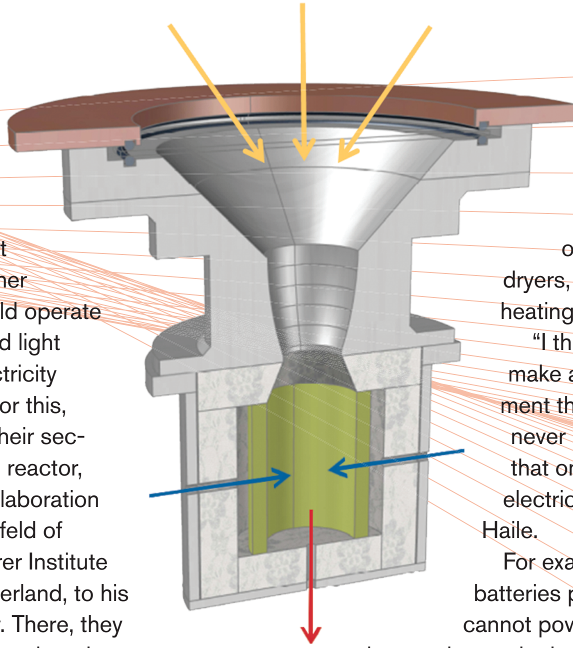
By "gave it a try," Haile means that she and her colleagues designed and built prototype reactors that can cycle ceria through the conditions required for fuel production. A first design used electric heating, and a second, more realistic design used a parabolic mirror to focus the sun's rays into an insulated, stainless steel chamber small enough to fit on a desktop.

Haile compares the solar concentration process to using a magnifying glass to start a fire.

To test their idea, the team supplied a stream of inert argon gas through the reactor while cranking up the temperature to about 1,600°C. At these temperatures, ceria pushes oxygen atoms out of its crystal lattice. The researchers then added some carbon dioxide, water, or both to the gas flow and allowed the reactor to cool to a relatively balmy 800°C. As the ceria cooled, it stripped oxygen atoms from the gas mixture and pulled them back into its crystal structure, producing carbon monoxide and/or hydrogen gas. Once the ceria was re-oxygenated to full capacity, it was heated back up and the cycle began again.

Hydrogen gas is a storable fuel on its own. But the carbon monoxide–hydrogen combo could be even more useful in the long run. Called "syngas" (short for "synthesis gas"), this mixture of two simple molecules is the raw material for making gasoline, jet fuel, diesel oil, or any other hydrocarbon your heart desires.

Experiments with the electrically powered prototype reactor showed that the material produced exactly the amount of fuel predicted by thermodynamic calculations.



But the real test would be whether the reactor could operate on concentrated light rather than electricity from the grid. For this, the team took their second-generation reactor, designed in collaboration with Aldo Steinfeld of the Paul Scherrer Institute in Zurich, Switzerland, to his solar laboratory. There, they could pour energy into the reactor from a wall of high-powered spotlights that produces heat equivalent to 1,500 suns.

During initial experiments, the "on-sun" reactor worked on almost the first try—a huge success in the research world. Its record-shattering fuel-production rates and unprecedented stability "really set a benchmark for the solar-fuel community," Haile says. "We did it without precious-metal catalysts, and in a pre-commercial design that actually demonstrates the complete system."

The team's highest priority now is to increase the process's efficiency. Says Haile, "We were hoping for 16 to 19 percent efficiencies, but we only achieved 0.7 to 0.8 percent. This was a bit disappointing, but we could see very clearly how to change the design to make the reactor much more efficient." The catalyst needs to be improved as well, says Haile. "If we can find catalyst materials that work at lower temperatures than ceria does, we can dramatically loosen up the design constraints on the reactor."

Haile believes that the thermochemical approach to tapping sunlight will play a major role in a sustainable energy future. Besides producing hydrogen and syngas, which are useful for transportation, this approach can be used to make methane almost as easily by tuning the reaction conditions and catalyst ingredients, she says. Methane is the primary ingredient in "natural gas"—used in many homes to power appliances like ovens, clothes dryers, and central heating.

"I think one could make a good argument that we will never have a society that only runs on electricity," says Haile.

For example, batteries probably cannot power jumbo jets, and even the best electric cars still take hours to recharge. "This means we need to make chemical fuels. So here it is. This is the way you make chemical fuels," she says confidently.

Haile does, however, point out that capturing CO_2 from the atmosphere to make fuels using sunlight energy remains a challenge. "If we make methane at a power plant and immediately recycle the CO_2 that it generates, then we have a 'zero carbon emissions' scenario and all is good," she says. "But if we make liquid transportation fuels, then CO_2 is emitted by cars, trucks, and airplanes and we haven't fundamentally solved the problem of climate change. This hitch is what keeps battery and hydrogen-fuel-cell vehicles important alternatives to conventional cars."

She also points out that this project is just a small part of her group's sustainable-energy research, most of which continues to revolve around fuel cells. "If we don't solve the problem of energy, life as we know it *will* change," says Haile. So while the energy dilemma continues to magnify, it's comforting to know that a search for the solution is in full focus. E&S

***Haile's ceria reactor research was funded by the National Science Foundation, the State of Minnesota Initiative for Renewable Energy and the Environment, and the Swiss National Science Foundation. The full results of the research were published in the December 24, 2010, issue of* Science.**

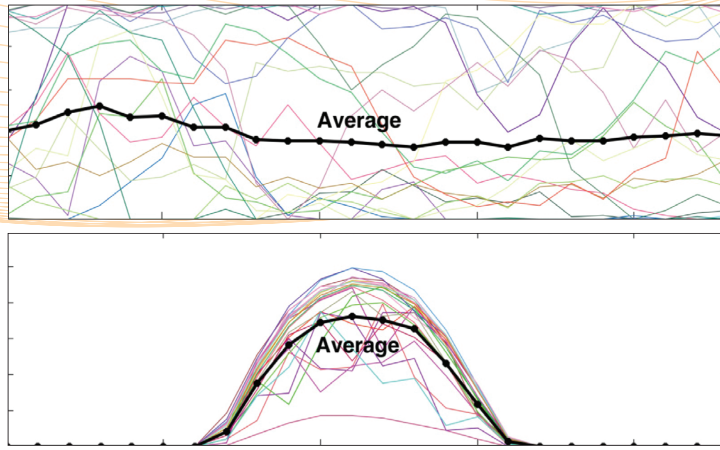
Greening the Grid

By Kathy Svitil

At any given moment, the world's population tears through 15 terawatts (TW) of power—that's 15,000,000,000,000 watts' worth of burning bulbs, humming air conditioners, lurching subway cars, spinning slot-machine wheels, and more.

In the United States, a paltry 8 percent of our power comes from renewable sources like solar, wind, hydropower, and biofuels. In theory, though, *all* of our power needs could be met, with ease. Harvesting the energy of just *one-fifth* of the winds gusting across Earth's land would net at least 70 TW of power. The sunshine we bask in? A whopping 340 TW.

So do we just blanket the landscape with solar panels and wind farms to solve our energy woes? Not exactly. We'd still have to get that energy into the electric grid—and that's no small task.



Connecting the wind belt to the power-hungry populace requires building power lines and other infrastructure, which requires a huge outlay of capital. The issue is similar for solar energy, which is more readily available in the southwest United States. The difficulties extend down to the local level, Chandy says: "The most effective places to get sunlight are where you have lots of flat roofs," such as the industrial areas of Ontario, California, "not downtown L.A., where the power is actually needed," he says.

But there's a larger problem. "Nature determines when the sun shines and when the wind blows," says Chandy, "so you have to take them when they're available. And if nature decides to make a calm and cloudy day? You don't get any energy." Winds gust and die; clouds come and go. Even on a good day, the power produced can "fluctuate widely, rapidly, and randomly," he says.

So how *do* you rely on something that's inherently unreliable? Chandy and fellow computer scientist Steven Low are working to make the electrical grid itself smarter, so that it's better able to predict routine variations—in supply *and* demand—and flexible enough to cope with unforeseen changes.

Our power grid is highly centralized, with more than 9,000 electrical generators connected through more than 300,000 miles of transmission lines. Every four minutes or so, the system evaluates power use and adjusts the supply to track fluctuations in demand. But a lot can change in four minutes, so the grid is designed with considerable excess capacity to ensure that sudden demand spikes—say, 111 million viewers simultaneously flipping on the Super Bowl—don't lead to blackouts.

Could the grid be made smaller? In an ongoing project, Chandy and Low have been simulating the power usage on Catalina Island, whose 4,000 or so permanent residents and

Winds gust and die; clouds come and go. So how do *you rely on something that's inherently unreliable?*

The most obvious difficulty is simply connecting the dots. The best places to capture solar and wind energy are often the least accessible. "Wind is not where the population is," says computer scientist K. Mani Chandy.

If wind were a crop, the "wind belt" would stretch from Montana and North Dakota south to New Mexico and northern Texas.

The country's population centers, in contrast, are located on the coasts.

Right: K. Mani Chandy (left) is the Simon Ramo Professor and professor of computer science. Steven Low (right) is a professor of computer science and electrical engineering.

Above: The electricity output of a wind farm (top) and a set of solar panels (bottom) fluctuates rapidly, randomly, and by large amounts over each day. Each colored line is one day of a typical month.

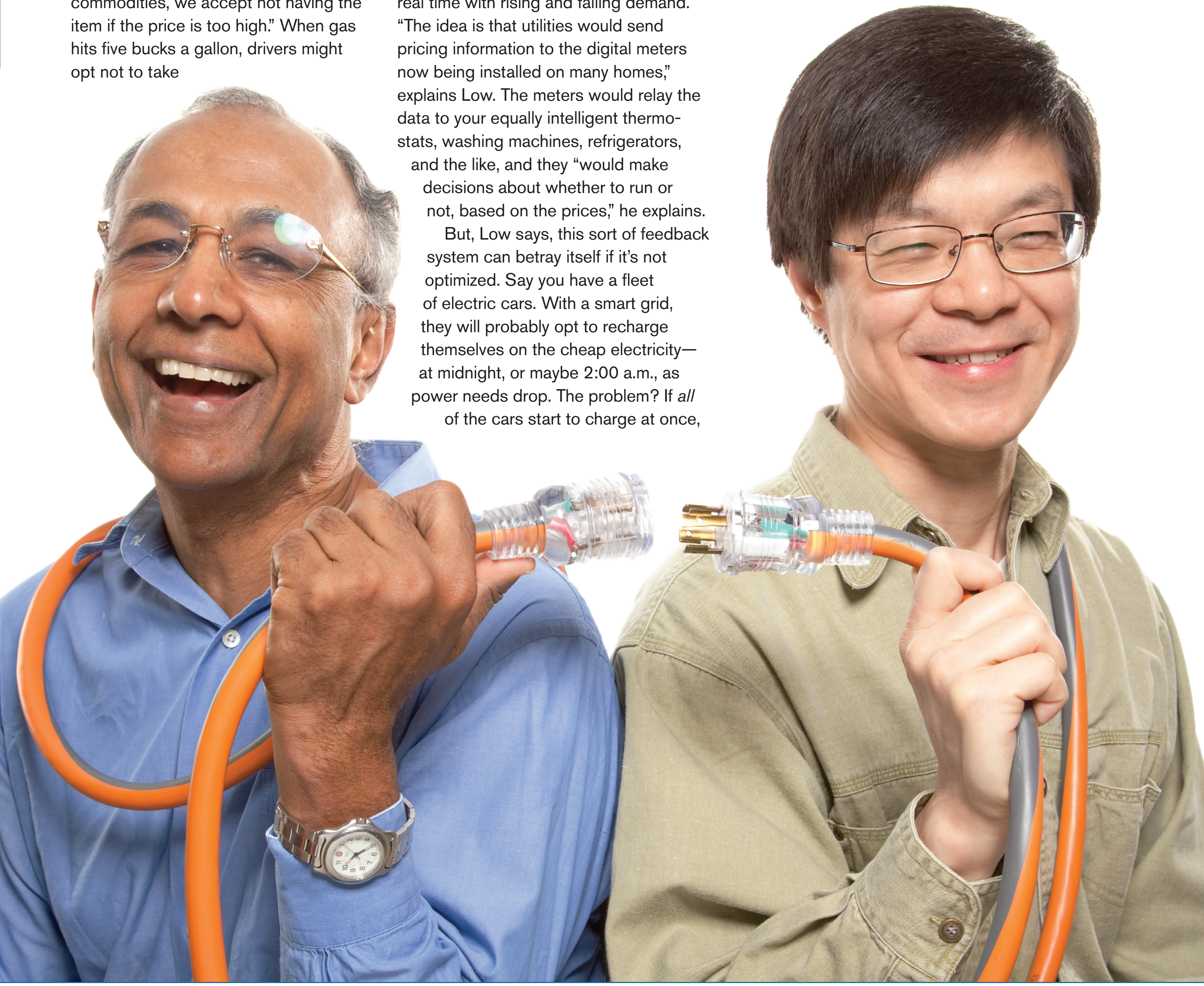
a seasonal flood of tourists now import their electricity in the form of diesel generator fuel via an hour-long boat ride. The mathematical model, which included real-world weather data *and* an adjustable tolerance for the risk of occasional blackouts—determined that the entire island could get by on half a dozen wind turbines, half a dozen football fields worth of solar panels, buffered by a few tens of megawatts of battery storage.

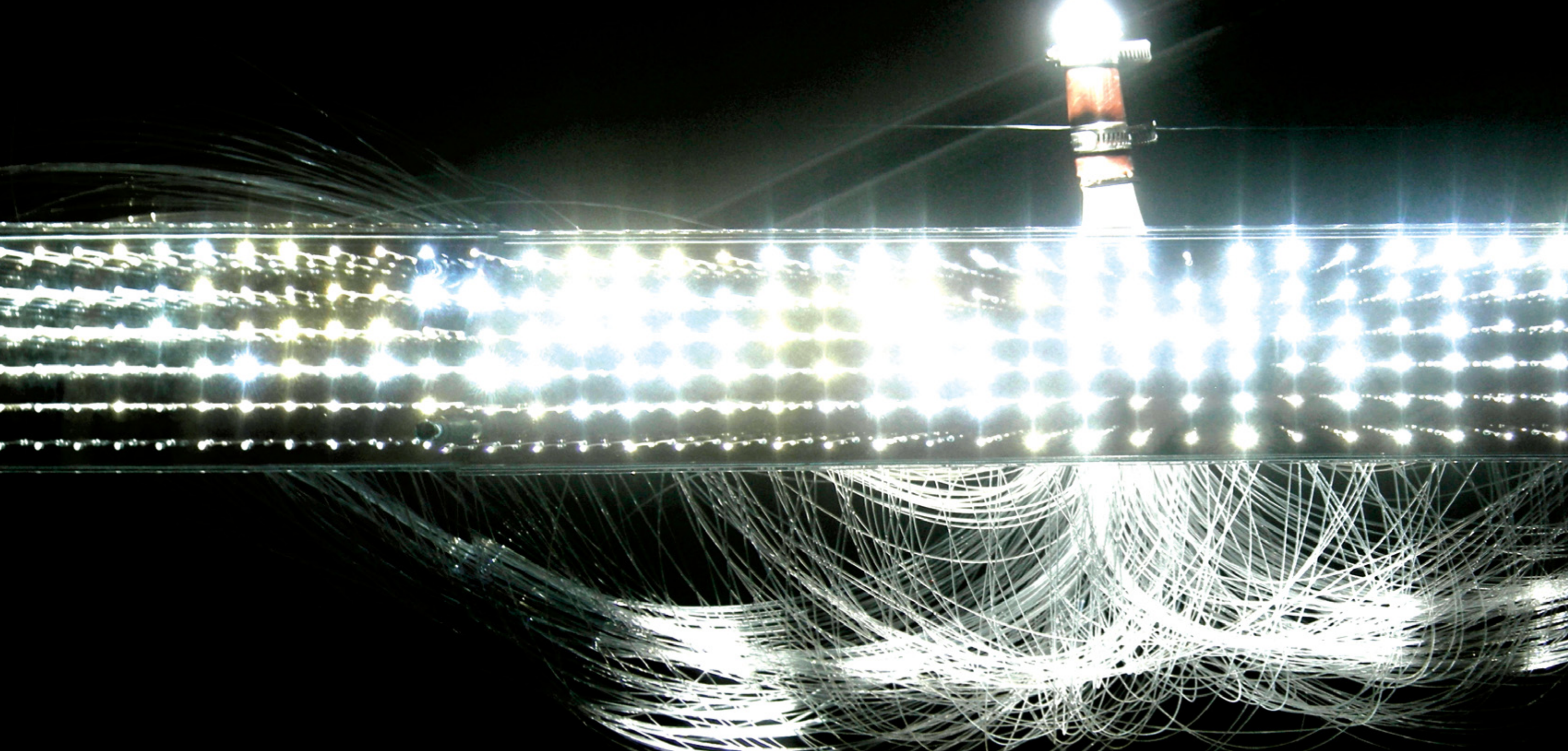
"Right now, we tolerate no risk. We flip a light switch, and the light comes on," Chandy says. "But with other commodities, we accept not having the item if the price is too high." When gas hits five bucks a gallon, drivers might opt not to take their car to the store—or might even hop on a bus. "What if that was applied to electricity?" he asks. Would people wait to wash their sweaty summer clothes in the evening, once the air conditioners are idle? By spreading energy use over time, he says, "the system can handle greater overall load."

Alternatively, instead of each individual consumer making these individual decisions, the system could make them for you. Chandy and Low are helping design the "smart grid" envisioned by the U.S. Department of Energy, in which the cost of residential energy would fluctuate in real time with rising and falling demand. "The idea is that utilities would send pricing information to the digital meters now being installed on many homes," explains Low. The meters would relay the data to your equally intelligent thermostats, washing machines, refrigerators, and the like, and they "would make decisions about whether to run or not, based on the prices," he explains.

But, Low says, this sort of feedback system can betray itself if it's not optimized. Say you have a fleet of electric cars. With a smart grid, they will probably opt to recharge themselves on the cheap electricity—at midnight, or maybe 2:00 a.m., as power needs drop. The problem? If *all* of the cars start to charge at once, the surge in demand they create will raise prices. The result? The cars will shut back off, creating another dip in demand that will again lower prices—and flip the chargers back on. "Part of the research we're doing here is to understand that feedback," he says. "That's absolutely crucial if we're going to be able to control it properly." E&S

The Catalina Island study is being performed under contract to Southern California Edison. Chandy's and Low's smart-grid research is funded by the National Science Foundation.





The Prodigal Sun

By Lori Oliwenstein

A Caltech building where scientists used to think about the origin of the universe is morphing into a place where they will ponder the fate of our planet. This summer, members of the newly created Ronald and Maxine Linde Center for Global Environmental Science will move into the former Robinson Laboratory of Astrophysics, reborn as the Linde + Robinson Laboratory for Global Environmental Science.

This renovation unveiled an opportunity that came in the guise of a problem. The building's centerpiece, though physically offset, is a solar telescope that was intended for Caltech cofounder and solar astronomer George Ellery Hale. The main part of the instrument is a contraption called a coelostat (SEAL-uh-stat), which sits with its associated hardware under a large white dome on the roof of the building. When in use, the coelostat's 36-inch-diameter mirror rotates to track the sun through an opening in the dome, sending the light it captures to a smaller mirror. That second mirror routes the light down an octagonal shaft, eight feet in diameter, that penetrates clear through the subbasement five stories below.

Built in the 1930s but not completed until 1968, the solar telescope had lapsed into obsolescence by the early 1980s. Now, with the Linde Center's posse of environmental chemists, oceanographers, and atmospheric scientists moving in, the question becomes: What could they possibly want with an old solar telescope?

Pretty much everything under the sun, as it turns out.

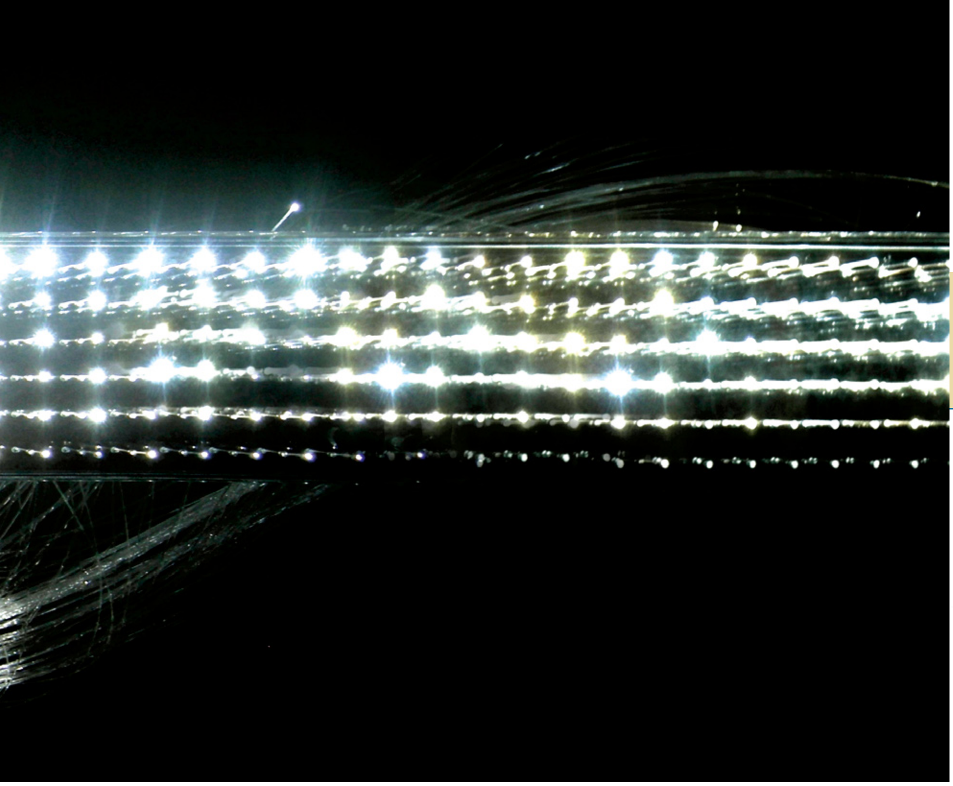
They want it to cool their building. They want it to shed light on their experiments, both literally and figuratively. And they want it to do what it's always done—keep the sun, the most bountiful renewable energy source we have, front and center in the minds of all who enter.

And so what elsewhere might have become a casualty of progress became part of it instead: an excuse to dream big, to not only embrace a very odd architectural feature but to reuse it, and the light it captures, in much the same way the building's original wooden doors and handcrafted light fixtures are being reused.

This waste-not-want-not reimagining of the coelostat and its solar shaft is part of the new occupants' gestalt, says Tapio Schneider, director of the Linde Center. These scientists want to actually practice what they're researching; after all, it's hard to solve global environmental issues in an energy-munching building.

"A central activity in the Linde Center is studying how the climate has varied in the past, as a key to understanding how it may change in the future," Schneider says. "Similarly, we wanted to use the scientific and architectural past of the building as we were reconfiguring it for the future."

Transforming these scope-in-the-sky musings into reality, however, would require the best of the best in several fields. Loisos + Ubbelohde, a firm specializing in energy efficiency and lighting design, teamed up with consultant



Left: Fiber-optic light fixtures will send sunshine into basement laboratories.

Returns

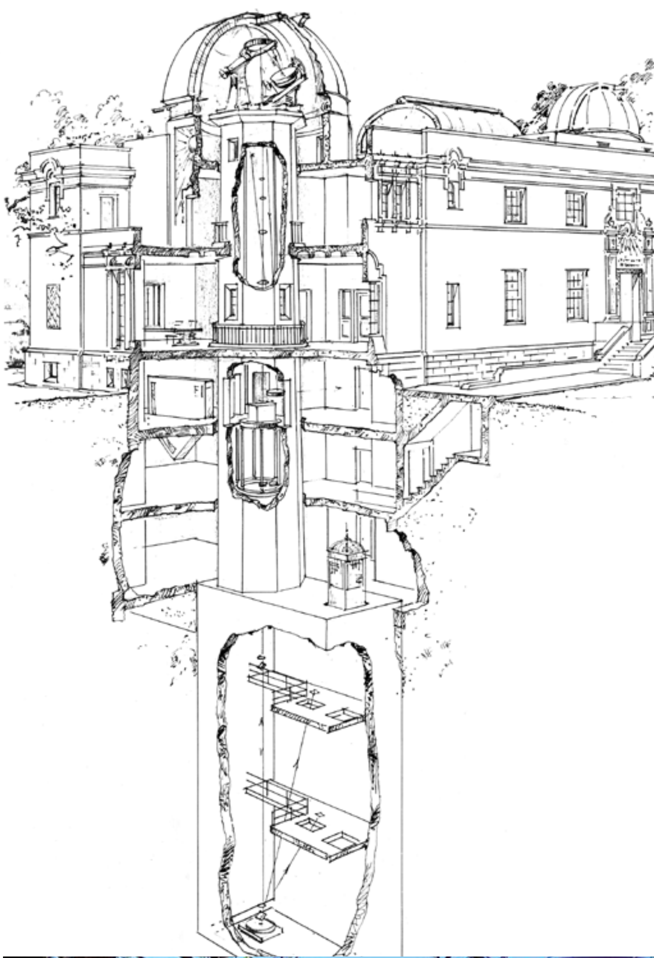
Richard Treffers—an expert in restoring old or abandoned telescopes—to really think through the telescope's reuse, and to automate its instrumentation.

"The controls hadn't been updated since it was built," notes Bart Hale (no relation), the Linde + Robinson construction manager with Caltech's facilities office. "They were completely nonfunctioning. Now they've been stripped out, and Richard has come up with a whole new set for us. It's remarkable."

That newfangled control system will check with a weather station on the roof, only kicking into gear and opening the telescope's impressive white dome when the sun is visible. When the dome's doors part, the coelostat will track the sun's movements—and the moon's as well, on nights when it's sufficiently visible—without human intervention and while taking into account such things as seasonal changes in the sun's path across the sky.

And, thanks to the good folks at the University of California's Lick Observatory, the images that are sent down the solar shaft will be as sharp and clean as possible, now that the mirrors have gotten their first-ever face-lift. "The technicians cleaned the mirrors' surfaces, and put a new reflective layer of aluminum on top, with a special overcoating," says Treffers. "Aluminum degrades, so you need that protective coating if you want the mirrors to survive another 80 years or more."

Once the sunlight is in the shaft, pretty much anything goes. Small mirrors will grab bits of the solar beam and redirect them onto a translucent glass window separating the shaft and the first-floor library, creating a real-time, safe-to-stare-at image of the sun that will be at least a foot in diameter;



The south facade of the Robinson Laboratory of Astrophysics featured a bas-relief sunburst just beneath the solar telescope's dome; like the scope itself, the sun was spared during the renovation and will remain as a symbol of the work done within.

Inside the dome, the coelostat awaits the return of its mirrors. The pedestal in the middle of the photo is for the 30-inch mirror that will send the sunbeam down the shaft. The 36-inch main mirror goes in the rotating mount at the bottom left.

through tubes into labs for use in various research projects; and via optical fibers into light fixtures.

LET THE SUN SHINE IN

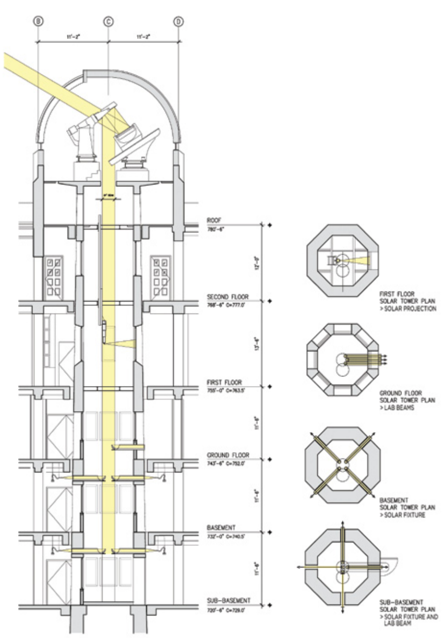
Exploiting natural light to illuminate an office or laboratory might not be stop-the-presses stuff in general; windows have been around for quite a while, after all. But in Linde + Robinson, the sunlight will be snaking into places it rarely gets to in other buildings.

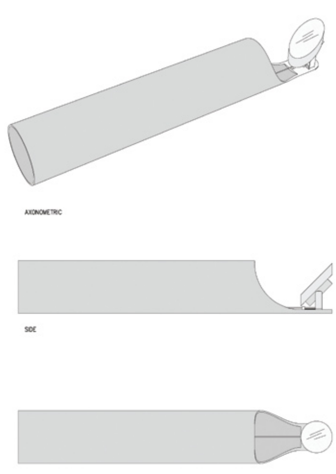
Loisos + Ubbelohde designed an "optical train" that will wend its way down to the subterranean spaces of the building. Arrays of small mirrors in the shaft at the basement and subbasement levels will divert daylight into fiber-optic bundles feeding ceiling lights in the adjoining laboratories. (During sunny days only, of course. On cloudy days, or after the sun goes down, it's back to those good old fluorescent lights.)

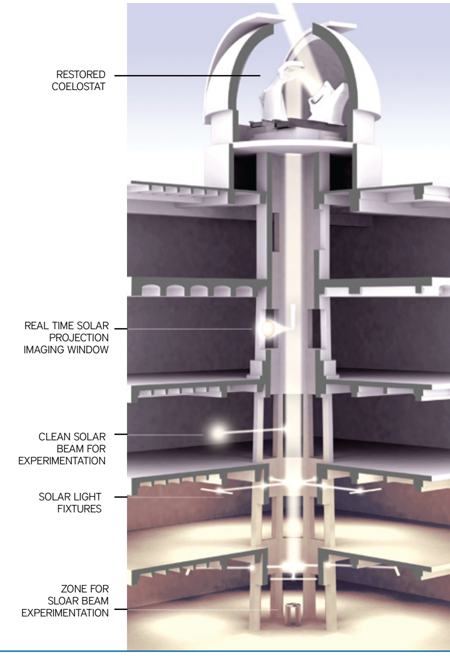
But the most exciting aspect of this solarpalooza is the prospect of using the light not just as *light*, per se, but as a test subject, as information, as an object for exploration. After all, this is the real thing: light from the sun itself. And it's right there, right at hand. Why squander the opportunity to put those photons to the test—whatever that test may be?

"During some of the early planning meetings, I remember asking about using the solar telescope to run photolysis reactions—using sunlight to break down chemicals—as opposed to taking the experiments up to the roof," says environmental chemist Michael Hoffmann. "The main idea was to work with actual solar photons in the lab rather than using artificial, lab-generated light."

To make that happen, another small mirror in the shaft will direct some of the sunlight through a "mirror tube" to an optical table in Hoffmann's ground-floor laboratory, thereby turning the sunshine into just another utility, along with nitrogen, compressed air, and vacuum lines. In other words, says Schneider, "After decades in which it went unused, the solar shaft is going to be re-lit. It will literally shed light on the future of our environment by providing a light source for investigating such questions as how smog forms, and by delivering spectra from which the composition of the atmosphere can be inferred."







PICTURE CREDITS
32–33, 33, 34 — Loisos + Ubbelohde; 33 — Caltech Archives; 34 — Lori Oliwenstein; 35 — Lance Hayashida

To that end, atmospheric chemist Paul Wennberg is adding the coelostat to the Total Carbon Column Observing Network (TCCON), a Caltech-managed program to monitor greenhouse gases. TCCON records solar spectra in the near-infrared region; the spectra are then teased apart to accurately determine the abundances of carbon dioxide, methane, nitrous oxide, hydrofluoric acid, carbon monoxide, and water in the atmosphere.

Despite the fact that Caltech runs TCCON, the campus hasn't actually housed any of its key devices until now. "It will be fantastic to have a permanent instrument here," says Wennberg, "and very nice to repurpose the coelostat. The modern instrumentation housed in the solar shaft will give us exquisite spectra of the sun rivaling those obtained from the original spectrograph that previously filled most of the basement. This new use of the coelostat is similar to its original function, except that what used to be the noise—the absorption by the atmosphere—is now the signal."

Meanwhile, over in Hoffmann's lab, researchers will be testing some of the light-to-energy conversion systems being developed by JCAP, the Joint Center for Artificial Photosynthesis (see page 22). "Using natural sunlight instead of the energy-inefficient mercury or mercury-xenon lamps that are now used in the lab has obvious advantages," Hoffmann notes. Sunlight is free, for one thing, and the results his lab gets will be a much more accurate reflection of the conversion systems' real-world performance.

GETTING TO THE BOTTOM OF IT

The innovations don't end with the light. Back in its heyday, the shaft opened into the "solar pit"—a vast, concrete-walled space 55 feet deep. The solar beam would hurtle down that entire length, eventually hitting one last mirror that would send it to a nearby laboratory, where the light that had begun its journey up in the dome would finally be resolved into an image of the sun up to 22 inches in diameter.

Today, the pit—now with waterproofed walls—is slated to become the centerpiece of an innovative, space-saving climate-control system. The pit will be filled with 50,000 gallons of water and, explains Hale, "at night, the water will be brought to the roof to cool to a mean chilled temperature of around 54 degrees Fahrenheit; during the day, we'll circulate that water through pipes throughout the building."

But that's not all: the pit will double as a cistern, collecting as much as an additional 10,000 gallons of water during the rainy season. "We'll use the rainwater to flush the toilets," says Eric Soladay of the Integral Group, the mechanical engineers on the project.

The chilled-water air-conditioning system will slash the amount of energy spent on cooling the structure by 80 percent; add that to the solar lighting and the host of other innovations and you wind up with a building whose overall energy use is expected to be just one-sixth that of a typical lab-laden edifice.

No other laboratory building in this country will be quite as energy efficient, says Schneider—in fact, these will be the first labs ever constructed in an existing historic building to earn a LEED platinum rating, the U.S. Green Building Council's top designation.

"This renovation does more than just nod to the building's history like an ancestor in a mantelpiece photo," says Schneider. "Instead, it makes creative use of that history to come up with solutions for the future." E&S

Tapio Schneider is the Gilloon Professor of Environmental Science and Engineering and director of the Ronald and Maxine Linde Center for Global Environmental Science.

Michael Hoffmann is the Irvine Professor of Environmental Science.

Paul Wennberg is the Avery Professor of Atmospheric Chemistry and Environmental Science and Engineering.

Architectural Resources Group, the project's lead architectural firm, specializes in historic renovations. Del Amo Construction is the general contractor.

The renovation of the Linde + Robinson coelostat was made possible by a gift from Foster and Coco Stanback. For information about how to help support the renovation of this building and the implementation of its unique environmental solutions, visit http://www.lindecenter.caltech.edu/.

Far left: A cross section of the solar shaft, and a set of plan views detailing the diversions the light will take on each floor.

Left center: Three views of one of the mirror tubes that will carry sunlight to the labs.

Left: A 3-D rendering of the shaft.

Right: The solar shaft, from below, in mid-renovation.

PICTURE CREDITS: Nina Zacuto Photography

From Rags to (Educational) Riches

By Katie Neith

Standing in front of a seventh-grade science class, Dave Zobel (BS ’84) poses a seemingly easy question. “What is light?” he asks the kids, who are assembled at round tables covered with strips of Mylar, pieces of plastic, a cardboard box, and various other materials. Half of the class raises their hands. The answer, however, is not so simple. Each kid has a different reply.

“Light is magical,” answers one student.

“Light is all colors,” says another.

Zobel explains that while *light* is a familiar word, it is not easy to define. And so begins a lesson on reflection, refraction, and magnification that is designed to foster curiosity. After all, science is really about having lots of questions, but not necessarily all the answers, he tells the students.

But Zobel is not a science teacher. In fact, he’s not a teacher at all. He’s a freelance science writer helping test an innovative program called Trash for Teaching (T4T). And the scraps on the table are just that—manufacturers’ remnants that otherwise would have ended up in a landfill.

Instead, the “trash” is prompting discussions: The students examine the brightly reflecting strips of Mylar, trying to figure out why their images appear inverted. Next, they hold up Petri dishes to different sources of light and talk about the colors they see reflected. Magnification is explored through the use of eyeglass lenses, and the cardboard box is used to explain the concept of a pinhole camera.

T4T collects clean and safe industrial castoffs and repurposes them for science and arts education, delivering materials to schools and offering teacher workshops on classroom instruction. Over 25,000 kids in the Los Angeles area have used T4T “trash” as part of a school project.

The nonprofit organization is the brainchild of Kathy and Steve Stanton, who run a local company that manufactures specialty packaging supplies. In 2004, their son—then three years old—began attending a Reggio Emilia preschool. Developed in Italy in the aftermath of World War II, the school’s method encourages learning by having young children explore “found” items in an unstructured way. The Stantons realized that their business created a lot of materials through its waste stream, so they started taking their unsalable by-products and overruns to the school for use in class projects. The multicolored ribbons, die-cut cardboard hearts, long cardboard tubes, and other items were hugely popular with the children, who found many ways to use them; energized by this enthusiastic response, the Stantons developed a pilot program and T4T was born.

“We saw T4T as a logical, simple, and environmentally friendly solution to the need for materials in education,” says Kathy Stanton.

For the past seven years, T4T’s Treasure Truck—filled to the brim with colorful materials and fueled by used vegetable oil—has visited L.A.-

Students in Armen Antonian’s seventh-grade science class at Sierra Madre School—part of the Pasadena Unified School District—get their first introduction to the Trash for Teaching unit on pinhole cameras. Nick Whiting holds the cardboard tea box that will become the camera’s body, while Brian Yik looks on.

area schools for a nominal fee, giving students full run of the truck so that they can cram shopping bags full of whatever gems the truck holds that day, and then create personal masterpieces. The organization is headquartered in a funky warehouse in Boyle Heights that is decorated with art installations built from donated “trash.” Bright blue bins are filled with discards collected from area businesses that donate everything from mass-produced scraps, like the tail end of fabric and foam rolls, to items that have already served their purpose in the manufacturing world, such as plastic tubes and cones used to spool ribbon.

Says Kathy Stanton, “Our ultimate goal is to help teachers, manufacturers, and environmentalists help one another by developing sustainable-reuse systems that encourage our kids to think critically and fuel their imaginations in all subjects by exposing them to non-traditional objects.”

A mutual artist friend introduced the Stantons to Zobel in 2009, and their conversations soon turned to whether this approach might be applicable to science lessons. “For more than a year I poked around T4T’s bins of parts aimlessly,” admits Zobel. “After all, how do you teach science in this century without rare-earth magnets and oil-immersion microscopes?”

But in late 2010, Intel officials offered to have their sales force assemble science kits as a community service project at their annual convention in Anaheim. They also generously provided funding to cover the collection, storage, and distribution of everything that would go into those kits.

“With a hard deadline looming, I was finally motivated to stop mulling and start designing,” says Zobel. Within a few weeks, he and Steve Stanton had worked out the concepts and drawn up the parts lists for four kits, and Zobel plunged into writing the teachers’ guides.

Zobel admits that putting the kits together wasn’t easy, especially since education is not his field. But fellow alumnus Paul Graven (BS ’85) put him in touch with Professor of Physics Jerry Pine, the director of Caltech’s Precollege Science Initiative (CAPSI). Launched in 1999, CAPSI has been studying hands-on methods for teaching science in grades K–12. Pine referred Zobel to Jennifer Yuré, a retired science adviser for the Pasadena Unified School District who gave him advice and helped drum up interest among local teachers.

“I have been working with Caltech scientists for many years now, and they always bring a different perspective to the table,” says Yuré. “It’s nice for educators to question each other and think about ways to engage students in science and thinking.”

In addition to hooking him up with the right people, Graven—along with a group of other friends—scoured the warehouse with Zobel, throwing out ideas along the way for fun projects.

“We had a lot of fun going through the warehouse and trying to think about different experiments we could do with the supplies,” says Graven. A longtime friend of Zobel’s, he became involved in T4T because it resonated with his desire to support science education by leveraging the resources Caltech has to offer.

“Paul stacked a couple of pieces of corrugated plastic on each other and said, ‘Hey, nice moiré pattern,’ and that

“Paul stacked a couple of pieces of corrugated plastic on each other and said, ‘Hey, nice moiré pattern.’” The warehouse also yielded such strange and wonderful things as surplus conical bobbins, specimen cups, and velvet discs, which have been incorporated into a lesson plan for building a tin-can telephone.

From left to right: Ryan Garcia checks out his reflection in a piece of Mylar.

Trash for Teaching founder Kathy Stanton examines the magnification properties of an eyeglass lens with Brock Vance.

Sarah Shaklan learns about reflection and refraction while playing around with a piece of Mylar.

was the genesis of the kit on moiré patterns," explains Zobel. The warehouse also yielded such strange and wonderful things as surplus conical bobbins, specimen cups, and velvet discs, which have been incorporated into a lesson plan for building a tin-can telephone—minus the can—which teaches the principles of engineering. By gathering rubber bands, cosmetic bottles, Styrofoam blocks, and plastic clips, among other items, they formulated a kit that explores the processes of inductive and deductive reasoning.

Zobel says the kits offer surprisingly extensive possibilities, and that teachers can easily adapt the lesson plans to cover as many or as few class periods as desired.

"Kids love to look at our stuff and try to figure out where it came from and why it was thrown out," says Zobel. "Isn't it wonderful that we can make something that teaches fundamental things that kids need to learn, but still has a 'cool' factor?"

Zobel isn't alone in thinking that the kits could make an impact on education.

"The kits are a nice 'extra,'" says Yuré. "They aren't a full curriculum, nor are they intended to be one, but they're a useful extension of regular classroom lessons."

"Using these kits requires more thought and exploration, reinforcing creative problem solving and out-of-the-box thinking," says Kathy Stanton. "Plus, the underlying message is always environmental."

According to Zobel, the kits are gaining traction—a success he credits to a growing list of volunteers who have become attached to the program. For example, Rebecca Constantino of Access Books—a not-for-profit that donates books to school libraries—heard about this project through Zobel and put him in touch with teachers and administrators from Santa Monica, Compton, and Orange County, all of whom are interested in signing up.

In addition, applied physicist Robert Chave, who used to work at Caltech and JPL, stopped by the T4T warehouse after hearing about the organization from a friend, and has since become an invaluable contributor to some of the lesson plans. And a conversation with Alycen Chan of the Caltech Y resulted in T4T being selected as a project for this year's Make A Difference (MAD) Day, an annual event held every April.

According to freshman Ted Xiao, who spearheaded the event, MAD Day is a time for the Caltech community to put down their research projects and spread out into the community to help others.

"I am an advocate for the health of our environment. Reusing our waste to help young students learn science is something I feel very strongly about," says Xiao. "After I heard about the mission of Trash for Teaching, I picked it as my MAD Day site immediately."

Looking forward, Zobel says he would love to design more kits. Even better, he'd like to train others to design kits, too. More kits equal more opportunities for children to learn science in innovative ways. "Ultimately, we'd love to reach as many kids as we can," he says.

T4T plans to hold a professional-development day, when teachers and administrators could visit the warehouse and learn how to use the lesson plans. Zobel and the Stantons are also working on audiovisual materials to complement the kits.

"The arts and the sciences are some of the first victims when budget cuts happen. T4T has proved that you can resuscitate a moribund art program by injecting low-cost materials," says Zobel. "Hopefully we can help science teachers, too, who often buy classroom supplies with their own money. Who knows—maybe soon we'll be able to reach beyond California and bring the whole nation our low-cost science kits made entirely of materials diverted from landfills." E&S

For more information or to get involved with Trash for Teaching, visit www.trashforteaching.org.

WE ASKED CALTECH ALUMS TO TELL US THEIR FAVORITE COMMENCEMENT MEMORY. HERE'S WHAT THEY HAD TO SAY:

I loved the sadly short-lived tradition of Caltech's all-male *a cappella* group Ecphonema popping up behind the podium just before the speech and letting fly with a well-rehearsed, speaker-specific "theme song"! One favorite was their amazing arrangement of the *NBC Nightly News* theme when Tom Brokaw spoke in 1999.

RAY BRADBURY [2000]: "You make a list this afternoon of the people who don't believe in you, and you call them tonight, and tell them to go to hell!"

The audience was always asked to wait until the last person walked before applauding. As a Zingman, I looked forward for four years to receiving all of the applause for my class. Imagine my surprise when I found out that someone named Zwick had taken an extra year to graduate!

When Bill Nye the Science Guy was our speaker in 1998, he mentioned a few things he had learned as the host of a children's science program. One gem was that, if you were going to get water dumped on your head, you could get through more takes before being completely drenched if you untucked your shirt. Later during the ceremonies, it started to rain pretty hard. Bill Nye, sitting on the stage, stood up and untucked his shirt! Way to keep your sense of humor!

In 1991, Jack Prater, who always hugged everyone, gave the speaker a big hug—the complication being that the speaker was the standing President of the United States, George H. W. Bush. That was great.

For the first time in 42 years, it *poured* down rain on my commencement (1995). The speaker said: "If you have received your diploma, you may seek shelter!" I was so lucky to have a last name that started with *A*!

In 1995, when the speaker said "Here at MIT . . ."
[*The speaker was alumnus Mark Wrighton, PhD '72, then the MIT provost.*]

Engineering & Science

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