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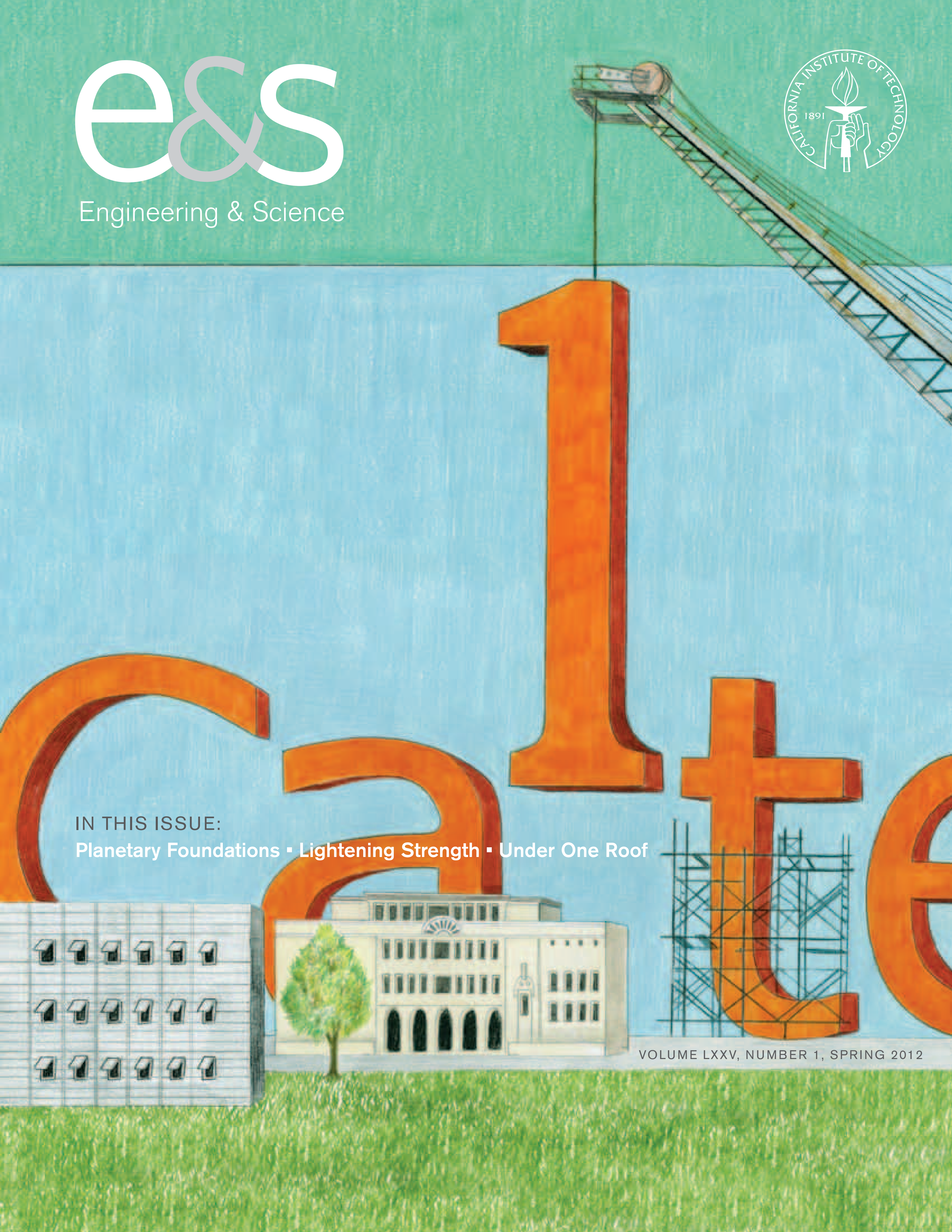

IN THIS ISSUE:

Planetary Foundations ▪ Lightening Strength ▪ Under One Roof

VOLUME LXXV, NUMBER 1, SPRING 2012

e&S
Engineering & Science

VOLUME LXXV, NUMBER 1, SPRING 2012

2 www.caltech.edu
Stay connected to campus, wherever you are.

3 From the President

4 Random Walk
Killer Asteroids ▪ Cell-Phone Medicine ▪ Watery Comets ▪ And More

14 **From the Ground Up**
BY KATHY SVITIL
Three of Caltech's newly minted assistant professors talk about their experiences as they work to recruit students, grow collaborations, and build a research program.

18 **A Sea Urchin's Life**
BY MARCUS WOO
With the help of the humble sea urchin, biologists are discovering how nature builds organisms from scratch.

24 **Big Small Things Happening Here**
BY KIMM FESENMAIER
Existing matter is being transformed into new materials by taking advantage of the strange and wonderful things that happen at the nanoscale.

32 **Caltech's Journey to the Center of the Earth**
BY KATIE NEITH
Intrepid researchers from the Seismo Lab are delving deep into the earth's interior to learn more about our planet's past and present-day internal dynamics.

38 **Alumni Impact**
BY KATHARINE GAMMON
Caltech alumni are building upon their academic experiences to lead innovative programs across the country and influence scientific thinking on an international level.

41 **Obituaries**
Nicholas W. Tschoegl
Aron Kuppermann

44 **Endnotes**
We asked alumni . . .

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Featured Videos

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youtube.com/user/caltech

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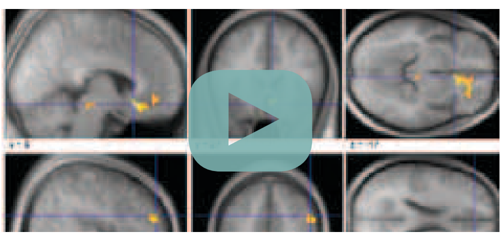
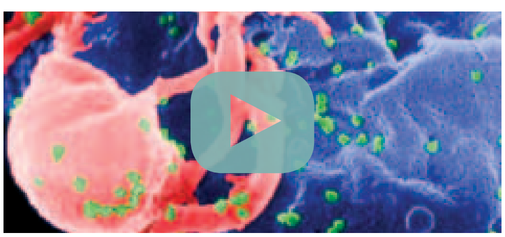


Watson Lecture: "Neuroeconomics: How Does Your Brain Make Decisions?"



Neutralizing HIV

2011 Draper Prize Lecture

HEADLINES

News and Information

today.caltech.edu

1

Caltech Nobel Laureate Named Top World Leader

2

Undergrads Honored for DNA Robotics Research

3

Caltech Profiles Notable Alumni

4

Caltech Ranked First in Engineering and Physical Sciences

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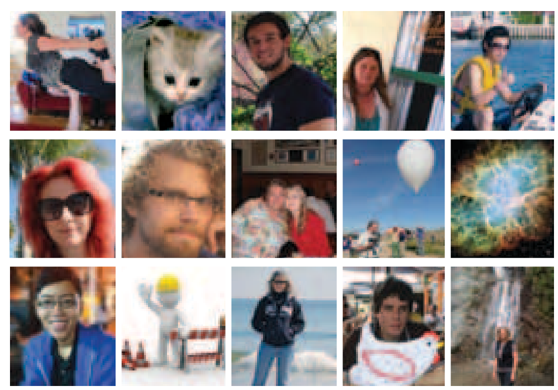

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Commencement 2012
June 15

Speaker: Elon Musk, founder and CEO of SpaceX and Tesla Motors

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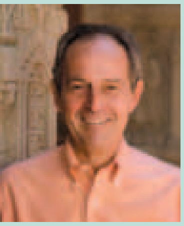
FROM THE PRESIDENT



Dear alumni and friends of Caltech,

At Caltech, we are always building the future.

You'll see our culture of innovation and invention throughout the pages of this issue of *E&S*, as you read about how new faculty build their emerging research programs, how seismologists build new models of Earth's core, how materials scientists are building at the nanoscale, and how biologists determine the ways genes regulate the building of a sea urchin from a fertilized egg.

But, as anyone walking around campus can see, Caltech is also building the future in a very literal, physical sense.

In January, we officially opened the doors of the Linde + Robinson Laboratory, which will house the Ronald and Maxine Linde Center for Global Environmental Science and the Terrestrial Hazard Observation and Reporting Center. Work continues on the Jorgensen Laboratory renovation; this revamped building will be the future home of two of Caltech's energy and sustainability research efforts—the Resnick Institute and the Joint Center for Artificial Photosynthesis.

When we build at Caltech, we build well—and we build "green."

That's why the Los Angeles chapter of the U.S. Green Building Council named our Annenberg Center for Information Science and Technology as the new-construction Project of the Year during their 2011 Sustainable Innovation Awards ceremony. The Annenberg Center also garnered the award for Indoor Environmental Quality, with our Warren and Katharine Schlinger Laboratory for Chemistry and Chemical Engineering grabbing an honorable mention as well. We are proud of these accomplishments, and equally grateful for our partnerships with the Annenberg Foundation and Warren and Katharine Schlinger, who have been long-time supporters of Caltech.

The generosity of our individual and institutional partners has enabled Caltech to accelerate scientific research and discovery and empower the next generation of scientific leaders. I look forward to continuing to build the future together.

Yours in discovery,

e&s

Engineering & Science

VOLUME LXXV, NUMBER 1, SPRING 2012

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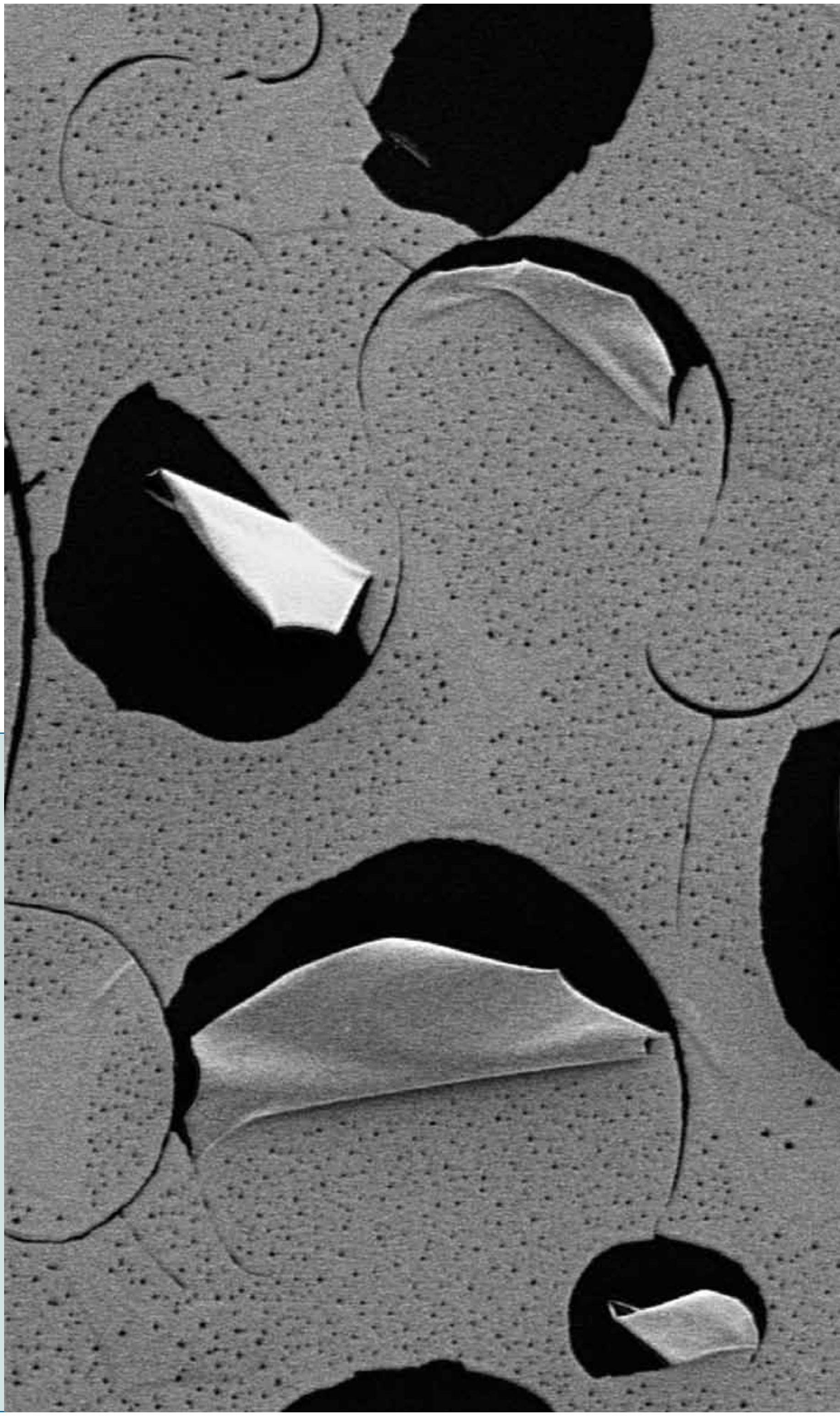
Random



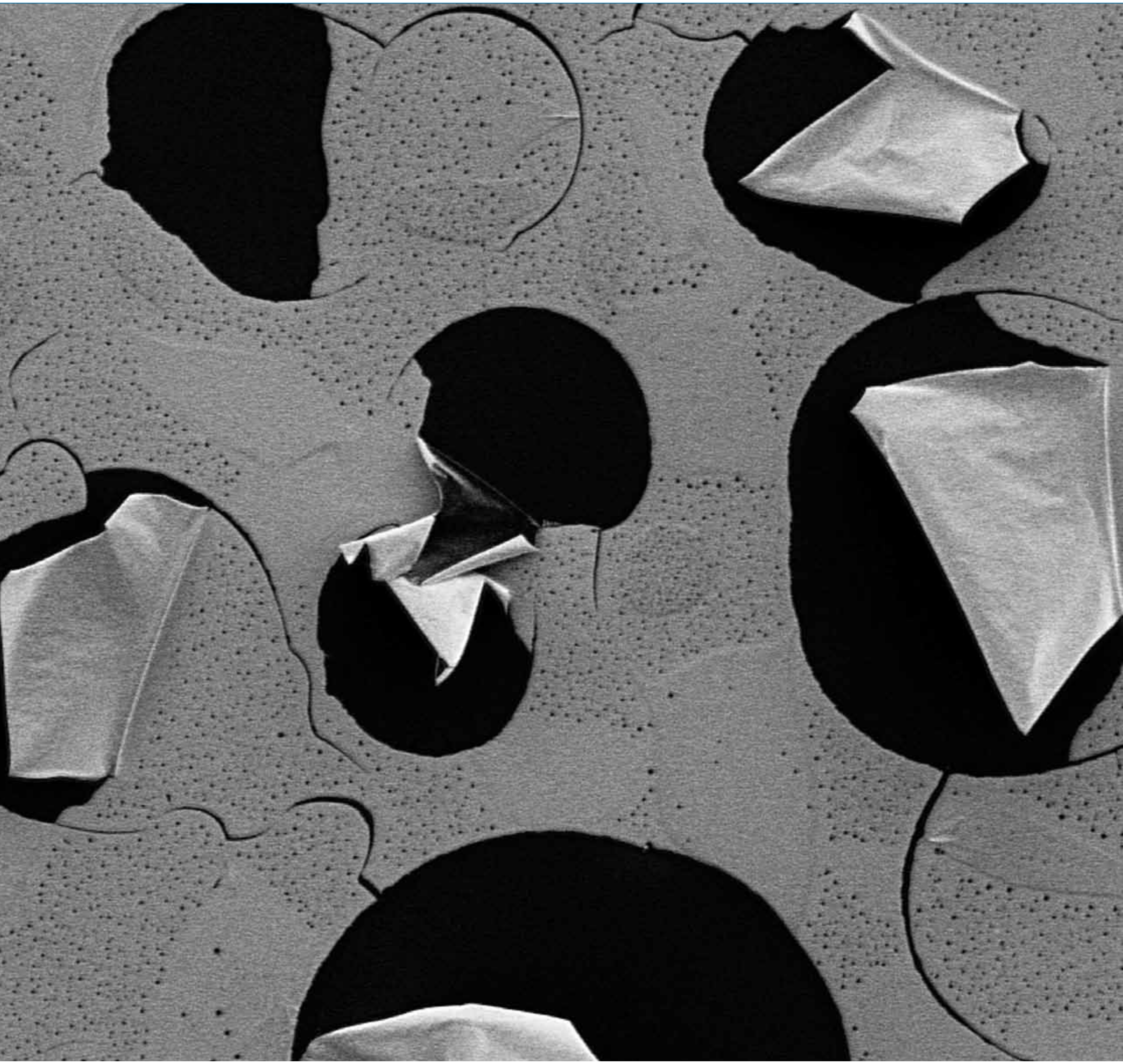
Art collector and author Gertrude Stein once remarked that "sculpture is made with two instruments and some supports and pretty air." The tiny sculpture shown here indeed relied on some pretty (hot) air to get its shapes. It is made from a thin film of gold, less than 100 nanometers thick, that was deposited onto Plexiglas and then heated. Due to differences in the thermal expansion of the two materials, this gold sample peeled up and twisted to form abstract art. This image, taken with a very powerful scanning electron microscope, was created by Dennis Callahan, a PhD candidate in materials science working in the lab of Howard Hughes Professor Harry Atwater.

For more of Callahan's artful images, check out his blog, Of Science and Art (ofscienceandart.blogspot.com).

If you have images you would like to share with us, go to eands.caltech.edu for more information.

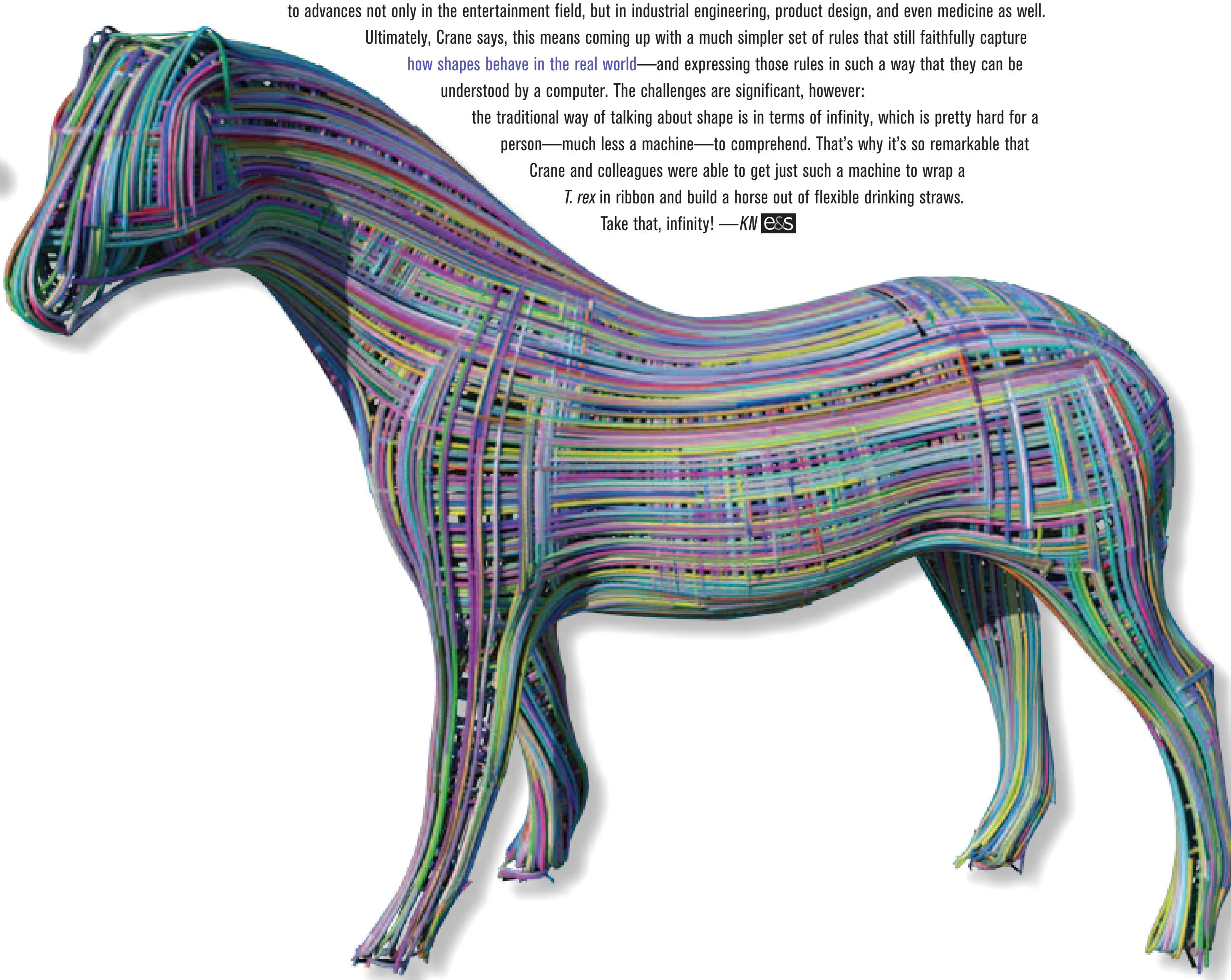
Walk

THINGS THAT CAUGHT OUR EYE . . .



CONQUERING SHAPES

Computer graphics have come a long way since early arcade games like Pong. But even from that seemingly simple beginning, the technology has been built upon an elaborate set of rules. Behind each computer-generated movie villain or video-game hero is a complex algorithm, or detailed list of instructions, that needs to be followed by the computer in order to create the intended image. Those lists are consistently being revised and revisited by people like Keenan Crane, a graduate student in computing and mathematical sciences, who designed the method that produced the *T. rex* and horse you see on these pages. His interest lies in knowing how computers represent and manipulate shapes—a line of inquiry called discrete differential geometry that could lead to advances not only in the entertainment field, but in industrial engineering, product design, and even medicine as well. Ultimately, Crane says, this means coming up with a much simpler set of rules that still faithfully capture how shapes behave in the real world—and expressing those rules in such a way that they can be understood by a computer. The challenges are significant, however: the traditional way of talking about shape is in terms of infinity, which is pretty hard for a person—much less a machine—to comprehend. That's why it's so remarkable that Crane and colleagues were able to get just such a machine to wrap a *T. rex* in ribbon and build a horse out of flexible drinking straws. Take that, infinity! —*KN* e&s



OCEANS OF WATER IN A PLANET-FORMING DISK

Water enough to fill Earth's oceans several *thousand* times over has been found in the planet-forming disk around a nearby star. The discovery, made by a team including Caltech's Geoff Blake (PhD '86) and Dariusz Lis and JPL's John Pearson, could help explain how Earth got its oceans. If other planet-building disks prove to be equally wet, "water-covered planets like Earth may be quite common," Lis says. The star, called TW Hydrae, is about four-fifths the mass of the sun and a mere 10 million years old.

While such disks are quite common, water vapor had never before been detected in the outer regions of one. The finding implies that the outer reaches of our own solar nebula could have been chock-full of ice as well. Such a large reservoir of water would have been crucial for the creation of Earth's seas, because the current theory of solar-system formation holds that water was scarce in the solar nebula's inner part, where our planet coalesced. "Water is essential to life as we know it," Blake says. "But the early Earth is predicted

to have been hot and dry." Earth's water, then, must have come from somewhere else. One likely source? Comets.

Comets, often called dirty snowballs, hoard most of our solar system's patrimony of water ice. A few million of them colliding with Earth in the early days could have brought in enough water to create our oceans. Such a scenario is not as implausible as it may sound—there was a tremendous amount of debris flying around back then, including as many as several trillion proto-comets. "These results beautifully confirm the notion that the critical reservoir of ice in forming planetary systems lies well outside the formation zone of Earthlike planets," Blake says.

The TW Hydrae measurements came on the heels of another discovery by Lis, Blake, postdoc Martin Emprechtinger, and others—that the deuterium-to-hydrogen ratio of comet Hartley 2's ice is similar to that of Earth's oceans, supporting the idea that the seas did come from the skies. (Deuterium is an isotope of hydrogen with an extra neutron in its nucleus.) In fact, the ratio suggests a very specific part of the sky: the Kuiper Belt, which begins just beyond Neptune's orbit and extends out to 50 astronomical units (AU) from the sun. (For comparison, Earth is one AU from the sun.) Previous measurements of comets from the Oort Cloud, a collection of trillions of icy bodies lying more than 5,000 AU from the sun, had shown a very different deuterium-to-hydrogen signature.

To make things even more interesting, the Oort Cloud's comets are believed to have been formed in the vicinity of the gas-giant planets Jupiter, Saturn, Uranus, and Neptune—that is, in the zone stretching from 5 to 30 AU—before being exiled into the very outermost precincts of the solar system by gravitational kicks from their bigger brethren.

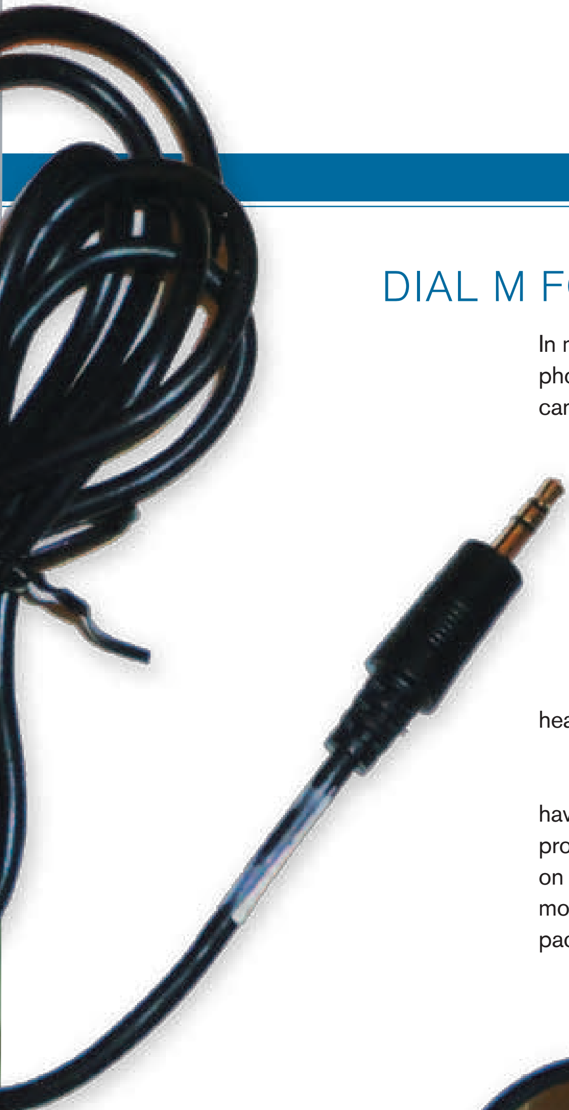
"The result . . . is consistent with the emerging picture of a complex dynamical evolution of the early solar system," says the paper.

Geoff Blake is professor of cosmochemistry and planetary sciences and professor of chemistry at Caltech. Dariusz Lis is a senior research associate in physics and the deputy director of the Caltech Submillimeter Observatory. The observations were made with the Herschel Space Observatory, a mission of the European Space Agency, using the HIFI instrument, to which JPL made significant contributions. Caltech's Infrared Processing and Analysis Center operates the NASA Herschel Science Center, which provides science and operational support for the mission. The Hartley 2 study was led by Paul Hartogh of the Max Planck Institute for Solar System Research in Katienberg-Lindau, Germany, and was published in the October 13 issue of *Nature*; the TW Hydrae work was led by Michiel Hogerheijde of Leiden University in the Netherlands and appeared in the October 21 issue of *Science*. —*MW* e&s

This artist's conception illustrates a storm of comets around a star near our own, called Eta Corvi. Evidence for this barrage comes from NASA's Spitzer Space Telescope, whose infrared detectors picked up indications that one or more comets were recently torn to shreds after colliding with a rocky body. In this artist's conception, one such giant comet is shown smashing into a rocky planet, flinging ice- and carbon-rich dust into space, while also smashing water and organics into the surface of the planet. A glowing red flash captures the moment of impact on the planet. Yellow-white Eta Corvi is shown to the left, with still more comets streaming toward it.

Spitzer detected spectral signatures of water ice, organics, and rock around Eta Corvi—key ingredients of comets. This is the first time that evidence for such a comet storm has been seen around another star. Eta Corvi is just about the right age, about one billion years old, to be experiencing a bombardment of comets akin to what occurred in our own solar system at 600 to 800 millions years of age, termed the Late Heavy Bombardment.

Scientists say the Late Heavy Bombardment was triggered in our solar system by the migration of our outer planets, which jostled icy comets about, sending some of them flying inward. The incoming comets scarred our moon and pummeled our inner planets. They may have even brought materials to Earth that helped kick-start life.



DIAL M FOR MEDICINE

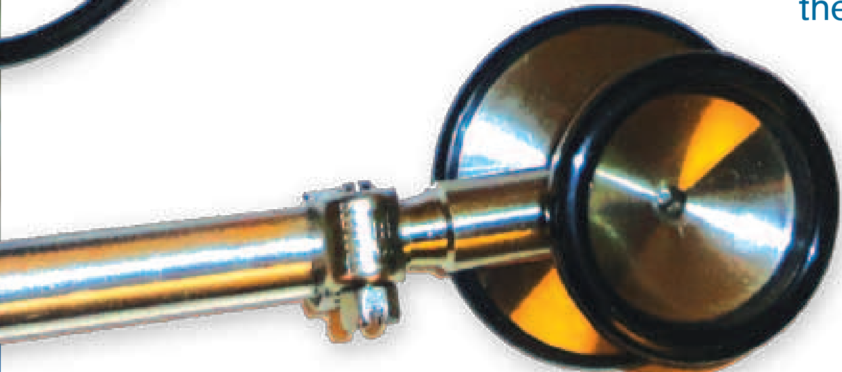
In many rural areas across the globe, people are much more likely to have a cell phone than a local doctor. Clinics are scarce in such remote locations, travel can be tough, and many laborers cannot afford to take a single day off work—all of which makes medical visits nearly impossible.

To address this lack of adequate health care, a group headed by Julian Bunn, of Caltech's Center for Advanced Computing Research, and Mani Chandy, the Ramo Professor and professor of computer science, is working to make the "10-cent checkup" a reality by building low-cost diagnostic devices that can be plugged into cell phones.

"We want to exploit cell-phone technology and the Internet to provide inexpensive health-care tests for the poor in remote rural villages," says Chandy.

Various students in the Summer Undergraduate Research Fellowship program have been working on the project for three summers now. Last year, four students built prototypes of a plug-in stethoscope and an electrocardiogram recorder. Other devices on the drawing board include a blood-pressure meter, a thermometer, and a heart monitor. The cell phone will relay the data to an Internet cloud, where a software package that students are also designing will sort the results into "probably normal"

"We want to exploit cell-phone technology and the Internet to provide inexpensive health-care tests for the poor in remote rural villages," says Chandy.



or "refer to doctor." The "referred" results would upload to the cloud, where doctors from virtually anywhere could review the data and determine whether the patient needs to be seen at a clinic.

Theresa Juarez, a senior in mechanical engineering, says she enjoyed the project because it deals with a tangible product and can influence people outside her immediate field. "It's more practical and hands-on," she says. "You end up getting a result at the end that you can play with and work and use, and it has the potential to actually make a difference, bringing adequate health care to places in the world that don't have it." *—KF/KN* e&s

15,500 FEWER THINGS TO WORRY ABOUT

Here's some good news, for a change: drifting around in our part of the solar system there are some 15,500 fewer asteroids than we previously thought that are big enough to wipe out a city.

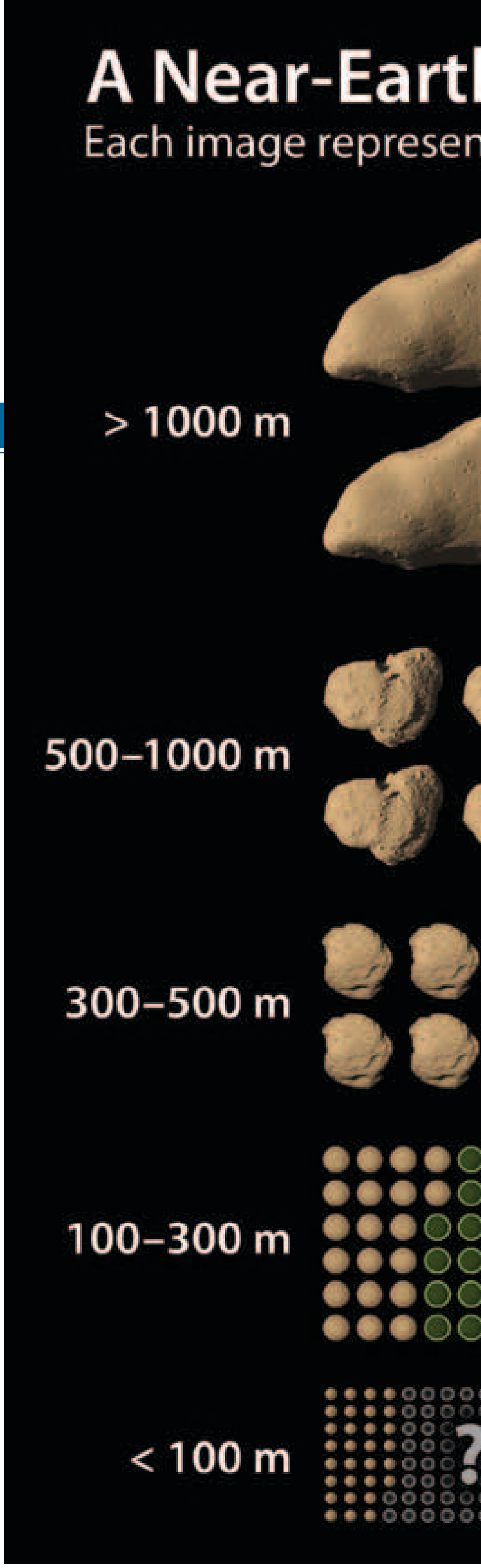
The Wide-field Infrared Survey Explorer (WISE) has just finished the best census yet of midsize and larger near-Earth asteroids, or NEOs—the space rocks that live well within Mars's orbit and occasionally come too close for comfort to Earth. This survey, called NEOWISE, "allows us to make a better estimate about the whole population," says JPL's Amy Mainzer (MS '01), NEOWISE's principal investigator and lead author of a paper describing the work in the December 20, 2011, issue of the *Astrophysical Journal*. "It's like a poll, where you ask a small group of people questions and use their answers to draw conclusions about an entire country."

The data, gathered from January 2010 through February 2011, provide far better estimates of asteroid diameters than previous visible-light surveys because infrared detectors sense heat rather than reflected sunlight. Many asteroids are quite dark—in fact, blacker than coal—but their temperatures depend primarily on their distance from the sun. The ones closest to us are thus relatively warm, averaging a balmy –73°C or so.

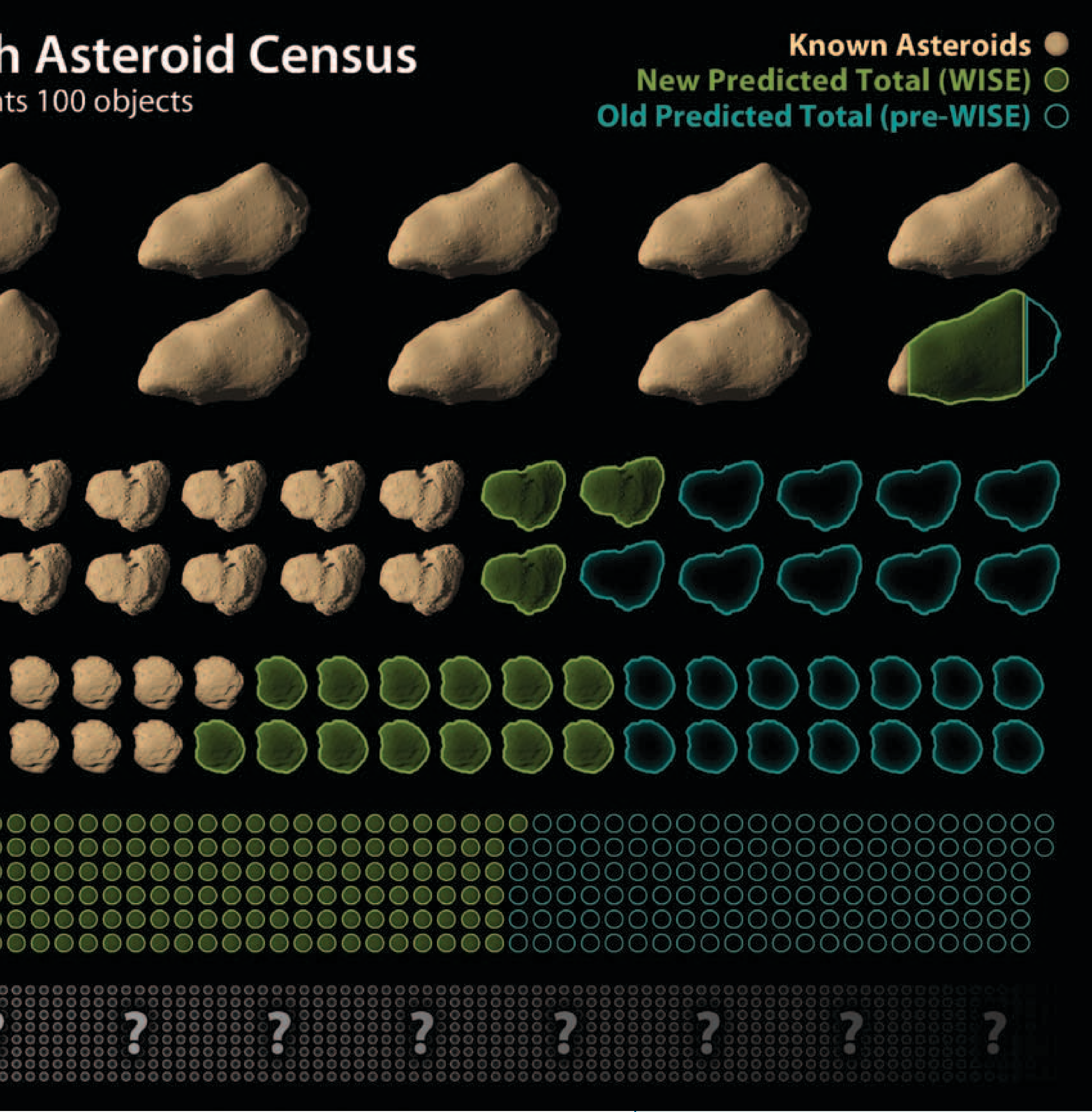
The NEOWISE survey suggests that all the NEOs in the 10-kilometer-diameter class—the dinosaur-killers—have been found. That's *really* good news, because most of the objects that we know of in this size range have had their orbits calculated to a high degree of precision for the next several centuries. None of the known ones are thought likely to draw a bead on us.

The analysis predicts that there are about 980 NEOs in the one-kilometer class—the size of a small mountain, and big enough to set civilization back quite a bit. NEOWISE's all-sky images allowed scientists to predict that about 910 of these have already been discovered, or 93 percent of the estimated number. None of the known ones are thought likely to draw a bead on us any time soon either. This finding fulfills a goal set in 1998 when Congress authorized NASA's Spaceguard program, whose mission was to be able to track at least 90 percent of the one-kilometer NEOs.

And finally, NEOWISE puts the number of midsize asteroids—those about 100 meters in diameter, or large enough to mean Game Over for any metropolitan area unlucky enough to suffer a direct hit—at roughly 19,500, which is about 15,500 fewer than the 35,000 previously estimated. About three-quarters of these remain undiscovered (or have not been spotted often enough to have their orbits accurately determined), so we're not out of the woods just yet. But identifying these asteroids as "near Earth" simply means that their orbital paths and ours are in the same general vicinity; the number of potentially hazardous ones that come *really* close to us remains unknown but is being investigated.



JPL operates the WISE spacecraft, which was built by Ball Aerospace and Technologies Corporation in Boulder, Colorado. WISE's telescope and camera



were built by the Space Dynamics Laboratory in Logan, Utah. WISE's principal investigator, Edward Wright, is at UCLA. Caltech's Infrared Processing and Analysis Center handles the spacecraft's science operations and data processing. —*DS* E&S

The NEOWISE survey looked at more than 500 objects larger than 100 meters in diameter. Each asteroid in this graphic represents about 100 space rocks. The known NEOs have been colored in; the outlines show how many NEOs were thought to exist before the survey, with the green outlines showing the new estimates based on the NEOWISE data. (Sizes of NEOs are not drawn to scale.)

FROM THE GROUND UP

By Kathy Svitil

The transition from postdoc to professor is a pivotal phase in an academic career—the moment when you strike out on your own, as it were. Three of Caltech's newly minted assistant professors—biochemist André Hoelz, computer scientist and economist Katrina Ligett, and physical oceanographer Andrew Thompson—tell us what it's like.

E&S: All of you must have come in with an idea of the research program you wanted to develop. How do you take that idea and make it happen?

KL: I feel I have two challenges getting started here. One is bringing in students and postdocs, and the other is fostering a connection between computer science and economics. I've only been here a couple of months, but so far it's good. There is a lot of support from both sides.

AT: I've got a challenge similar to Katrina's. I do oceanography . . .

E&S: There's not a lot of that here.

AT: Yes, that's exactly the point. It is not traditionally something Caltech has done, but there's a movement now to better understand the earth's climate, and the ocean is an important part of this system. So when I was looking at coming to Caltech, the idea of being "*the* oceanographer" was an exciting prospect. I'm a physical oceanographer—I studied engineering as an undergrad, and I use fluid dynamics to understand how eddies of all sizes redistribute heat and nutrients on a global scale. Usually you are surrounded by other oceanographers; if you have questions, you go down the hall, and there's likely that area of expertise. It is very different here. I've been in the library getting chemical and biological oceanography textbooks, because if I'm going be effective here, I need that broader background. Recruiting graduate students will be a challenge, because if someone says, "I want to do oceanography," they may look to Woods Hole, Scripps, the University of Washington. I'll need to attract students who came to Caltech to do physics but are interested in the environment. It will take some time to build that up, but long-term, by working with a broader group of people, I will be able to do research here that I might not have been able to do elsewhere.

AH: You don't step on anyone's toes here . . .

AT: [laughing] There's not that problem. There are no toes to step on!

E&S: To Katrina and Andrew: Did you have any reservations about coming here, because there aren't people who are doing exactly what you are doing?

KL: There's a growing number of people working at the intersection of computer science and economics, but it's not very many, and there are actually very few places anywhere where there is substantial interaction between the two fields. So this is a rare opportunity rather than a risk.

AT: It was certainly something that I thought about a lot. There is a strong oceanography group up at JPL that does a lot of satellite sensing of the ocean, which is where most of our data comes from, and I did my graduate work at Scripps, which is reasonably nearby, so I felt that there were people I could see on a fairly regular basis, even if they aren't down the hall.

AH: Mine is a totally different story. My work is essentially a continuation of a structural-biology project that I started seven years ago at the Rockefeller University.

E&S: Caltech is pretty well known for structural biology . . .

AH: Yeah, this is the place to be for structural biology. There is a very strong tradition that goes back to Linus Pauling and the correct proposal of the alpha helix and beta sheet as the primary structural motifs in protein structure. We're sort of a little family—we have shared group meetings, shared lab meetings, and journal clubs. The synergistic effect was one of the big attractions. I had other very prestigious offers that lost out because of that intensity and community. Another major factor was the superb infrastructure for X-ray crystallography—the Molecular Observatory—which was established with generous support from the Gordon and Betty Moore Foundation.

E&S: What is the biggest challenge for you?

AH: Moving from one place to another is always risky until you get a critical mass of people that can actually do the

KATRINA LIGETT

agenda, and helping to direct your portion of the field's research.

AT: It's a little bit scary, right?

KL: [laughing] Yeah!

AT: As a professor, if you're working on a project and it doesn't pan out, well, you've probably got two or three other projects going on at the same time, and it's fine. But if you give it to a student, and it fails, it's a big deal.

AH: That's why I said that it's very important to generate an environment where people help each other. You cannot bail out every single person. The lab has to regulate itself.

E&S: It seems like that would be a challenge for all of you. I imagine that you're all control freaks in some way, because of where you are.

AH: Letting go is the most important thing. You have to let people make their own mistakes. You would like to put a

science. And that's where most of my effort has been. I would say the biggest consideration has been generating a group spirit, and a lab culture that is supportive rather than highly competitive. It takes a great deal of energy to generate.

E&S: How much did Caltech's reputation factor into your decision to come here?

AT: It is certainly a well-respected name. Graduate students associate Caltech with a very high standard. When you're starting up a research group, you want to make sure you have very good students, and students require a lot of time. It's a big investment. If you have good ones, then you see a larger return on that investment than otherwise.

E&S: As graduate students, you work on particular projects, with a particular goal in mind. I imagine it's a different mindset when you become a professor and suddenly have to look at a much longer timescale.

AT: As a graduate student and a postdoc, I could look at a problem and say, "This is what I can do, I know how long it will take, and I know I have the skills to do it." But when you run a research group and devise projects, you have to factor in how long it will take someone else. Will they be able to learn the techniques necessary to do it? What is a reasonable time frame? Will it be suitable for a PhD? That's something I haven't had much experience with, and I think it will be an interesting challenge.

E&S: [To Katrina] You're nodding.

KL: Yeah, there's definitely a transition from working on problems to laying out a research agenda to figuring out how a whole team of people fits into that

ANDRÉ HOELZ

bridge over every single hole that they could fall in, but that's impossible. In the end, you go crazy. You may know exactly how *you* would do it, and how to get there the fastest, but this is not the only way. That's why it's absolutely true that you need to have very strong students, because they ultimately carry the lab. They know all the techniques, and they train the next generation that comes in.

E&S: Is it scary, though, worrying, "Do I have the right people?"

AT: That *is* scary. I feel this pull between getting people in and getting a research program started, and taking the time to be sure I get the *right* people in.

KL: It's a big investment. It's a big risk. You want it to be the right people. They are going to set the tone.

E&S: How will you know when you get there, when you've built the program that you want?

KL: I don't think it's ever going to be stable, where you think, "I've arrived!"—particularly when you're talking about a handful of people. From year to year, you'll have a slightly different mix of people, in slightly different places.

AH: You always have to keep reinventing what you are doing, and the moment you are not doing that, you will be phased out. I think there should never be an endpoint. For a scientist, it would be a little bit sad.

AT: Like Katrina said, I don't think you ever say "I made it, it's done." But it will be really exciting to get to the point where people come to you and say "I've seen your research, I have a bit of a different background and think there will be some nice overlap there," and you can say, "Yes, I'd love to bring you in because I'll be learning new things as well." That will bring a lot more diversity to the group.

That's something you can do at Caltech, because it is a small place and you've got all these interactions that wouldn't occur being with people doing roughly the same thing.

E&S: Is it intimidating coming to a place like Caltech because it is so small?

AH: And so accomplished.

AT: It is intimidating, but that's exciting as well.

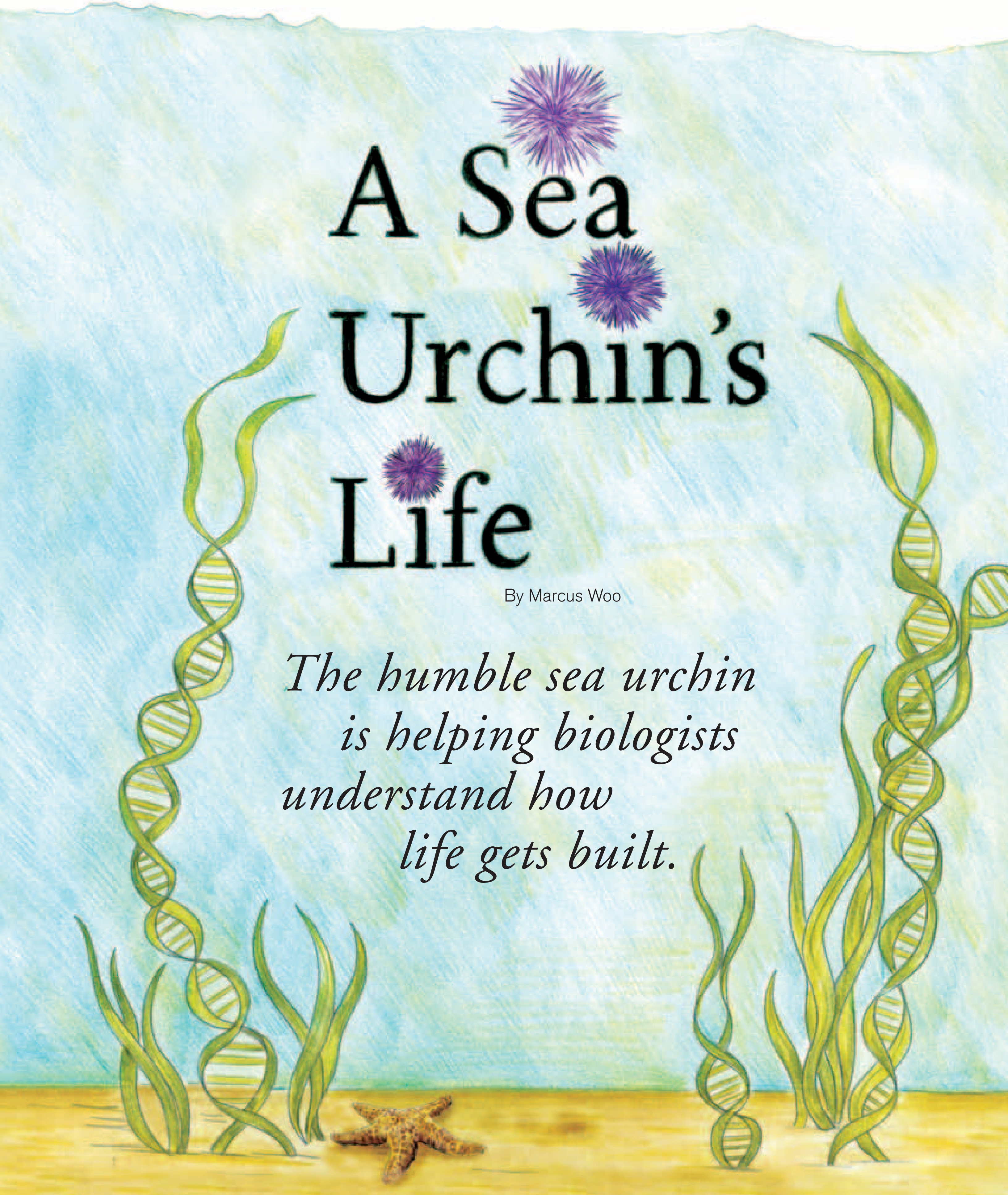
AH: I think it is inspiring. Ultimately, you want to have an environment where you strive to be better. It's certainly not for somebody with a weak personality. I think everybody here has done something great, and everybody has a great shot at doing something outstanding. But it doesn't mean you don't worry, "I hope I don't blow it." [laughs] E&S

ANDREW THOMPSON

A Sea Urchin's Life

By Marcus Woo

The humble sea urchin is helping biologists understand how life gets built.

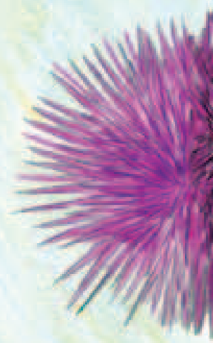


It's spawning season for the purple sea urchin. A female has released a milky cloud of millions of tiny eggs; her male counterpart has released millions of sperm, which swim toward the eggs.

When egg and sperm meet, it will mark the beginning of an intricate and complex process of development that will not only result in a long-lived, seafloor-dwelling adult sea urchin, but will also provide a window into the ways in which all organisms—humans included—go from egg to embryo to adult.

Indeed, for over a century, sea urchins have been helping scientists piece together the whys and wherefores of embryology. In developmental biologist Eric Davidson's lab at Caltech, biologists have been studying the development of sea-urchin embryos for 40 years, thereby helping to unfold one of the most important origin stories of all—how a fertilized egg transforms into a complex organism.

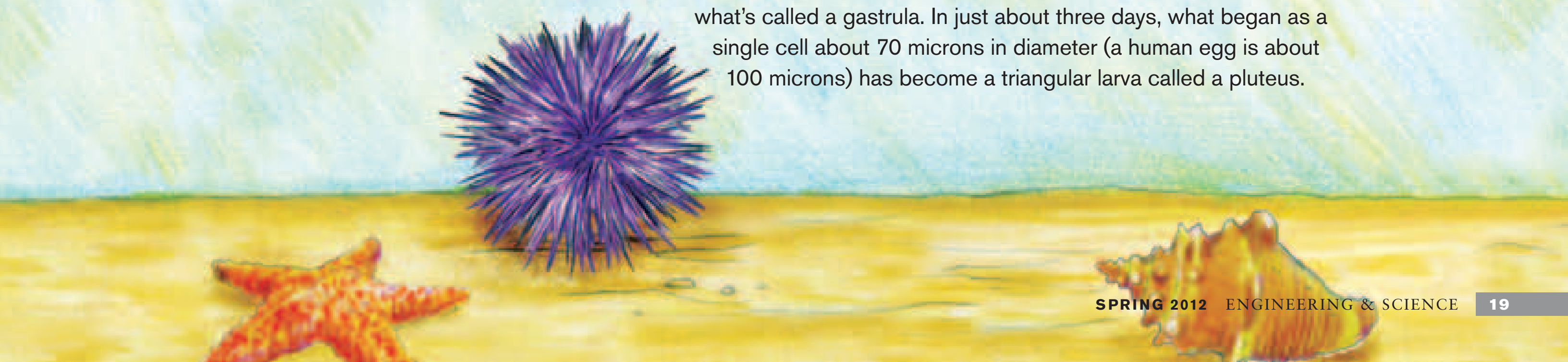
Much of what biologists know today about fertilization, embryology, and development they know thanks to the sea urchin. For example, sea-urchin research in the early part of the 20th century helped scientists discover that heredity is rooted in chromosomes, the folded structures of DNA and proteins that carry an organism's genetic information.



Over the past few decades, Davidson and his colleagues have worked out the principles by which the sea urchin's genes control its development. In 2006, researchers at the Human Genome Sequencing Center at the Baylor College of Medicine sequenced the genome of the purple sea urchin, and a team of 240 researchers from 70 institutions—led by Davidson, Caltech biologist Andrew Cameron, and others—analyzed and annotated it. This achievement has been crucial in helping scientists pinpoint the exact mechanisms behind the organism's development. And with recent advances that allow biologists to analyze hundreds of genes simultaneously, Davidson and his colleagues—together with biologists around the world—are unraveling the fundamental basis of development with a level of detail that was never possible before.

GROWING A SEA URCHIN

Under a microscope, the cells of a developing sea urchin look almost translucent, each containing a visible nucleus and hairlike cilium, which provides locomotion to the cell. But, at the molecular level, there's a lot more going on than meets the eye. During the first few hours after fertilization, the cells of a sea-urchin embryo divide synchronously, forming a hollow sphere of cells called a blastula within about 12 hours. By then, the cells will have started to separate into the precursors of the specialized types that will form the completed embryo: some will form the muscles, some the skeleton, some the nervous system, some the immune cells, others the gut. By the time it reaches the 24-hour mark, the embryo will have become a lot more complicated. It is now composed of about 500 cells, with the interior cells already expressing the genes needed to form the skeleton. At about 30 hours postfertilization, an indentation forms on the outer surface of the sphere, producing a cavity that later elongates into a tube, becoming the gut; the tube's ends become the sea urchin's mouth and anus. This process marks the transformation from blastula into what's called a gastrula. In just about three days, what began as a single cell about 70 microns in diameter (a human egg is about 100 microns) has become a triangular larva called a pluteus.



When Davidson arrived at Caltech in 1971, he already knew that to understand each and every one of these developmental milestones in the most fundamental way possible, he would have to explain how they're encoded in the "letters" of the double-helical DNA molecules of which the genome is composed.

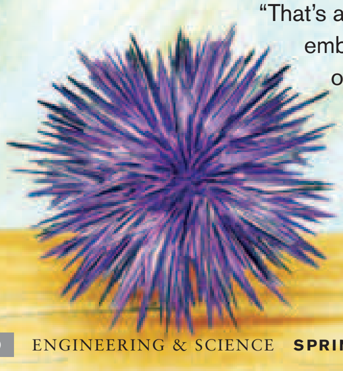
It is the genome that controls any organism's form and function. It is the genome—specifically, the interplay between genes in that genome—that determines that we humans will have two legs and two opposable thumbs, that elephants will have trunks, that turtles will have shells. It is the genome that dictates which cells of the embryo will become the gut, which will turn into muscle, and which will form the skeleton.

But the genome is more than just a blueprint—the genes responsible for development are more like a computer program that tells the organism how to build *itself*. As Davidson explains, it's like a building that starts off with a single brick that can multiply into many bricks, which then can assemble themselves into walls, form a roof, and grow all the necessary wires, pipes, and fixtures.

A PROGRAM FOR LIFE

Davidson's basement office is lined with shelves of books; his desk is covered with papers. Intricate line drawings of sea urchins adorn the wall. On his computer screen, he pulls up an image of about 900 transparent, identical-looking sea-urchin plutei. For most people, it might be just a pretty picture. But for a biologist like Davidson, it encapsulates one of the fundamental facts of life: that the genome defines an organism.

"That's a field of sea-urchin embryos," he says. "Every one is exactly like every other one. Once you look at that, you know development is a hardwired, programmed process." In other words, since every embryo looks like the one right next to it, they all must be operating under the same set of rules—the program for embryonic development that's resident in their genomes.



Over the last decade, Davidson's group has made tremendous progress in figuring out how the sea urchin's genes control its development. As it turns out, you can engineer a sea urchin to take on certain genetic traits simply by injecting those genes into its egg. And, perhaps most importantly, while reproduction in the wild is a game of luck, it's pretty easy to make large numbers of normally developing purple sea urchin embryos in the laboratory.

To do this, you first stick a needle into the underside of an adult sea urchin, through a soft spot just next to its mouth, and inject a solution of potassium chloride. The solution triggers the muscles in the sea urchin's reproductive organs to squirt out eggs or sperm, depending on the animal's gender. Then you just introduce the sperm to an egg and let nature do the rest.

Using a number of different techniques, beginning with these simple procedures, Davidson and his colleagues recently showed definitively that gene regulatory networks—interconnected webs of genes that control other genes—dictate development. Regulatory genes are segments of DNA that encode proteins that recognize certain DNA sequences and thereby tell other genes to turn on or off.

When a gene is on, the information encoded in its sequence of letters is used to produce a protein with a specific biological function—a process called gene expression. Sometimes, specific classes of genes have the job of regulating other genes. Ultimately, these genetic switches form a network that controls the expression of every gene that encodes the proteins responsible for the organism's structure and function. This allows a cell to "know" that it's meant to form a mouth, essentially because its mouth-forming genes are turned on.

"The essence of how you get from an egg to a complicated organism lies in those genes going on and off in different cells at different times," says Cameron, who is also the director of the Center for Computational Regulatory Genomics at Caltech. In fact, he says, it's the regulatory interactions between genes—rather than the genes themselves—that lie at the heart of what makes you a sea urchin

Left: Eric Davidson's computer screen features an image of adult sea urchins.

Below: A sea-urchin larva, called a pluteus, is about half a millimeter long. After drifting in the ocean for two to three months, it settles on the seafloor and transforms into its spiky adult form.

instead of a sea star, or a human instead of an elephant. "Different regulatory genes go on in different places at different times," Cameron explains, "and you get a nose instead of a trunk."

MAPPING IT ALL

In order to fully understand how gene expression is regulated, you need the entire genomic code of the creature you're studying—in the case of the sea urchin, that's 23,000 genes, plus their control sequences. And that's precisely what biologists at the Human Genome Sequencing Center at Baylor pinned down in 2006. Davidson and Cameron helped coordinate the program and organized the interpretation of the sequence. Armed with the sequenced genome, researchers can now analyze every line in the genetic program. "This is clearly the most fundamental way to look at the developmental process," Cameron says. "You can't get any more basic than that, can you? You're right there in the molecules and the DNA."

Of those 23,000 genes, a few hundred are regulatory genes—the roles of which need to be uncovered, one by one, if you want to completely understand how a fertilized egg becomes a purple sea urchin.

There are a number of ways to go about this sort of genetic treasure hunt. If you're trying to figure out if one gene holds sway over another, you can use a specific molecule that will turn that gene off and see how other genes are affected. Researchers in Davidson's lab are using this so-called perturbation method to analyze the effects of each regulatory gene on all other regulatory genes operating in each tissue of the developing embryo, and thus obtain information about all the gene interactions in the network.

These sorts of high-throughput methods enable researchers to analyze the flood of information encoded in a genome thousands of times faster and much more cheaply than they ever could before, says Davidson. "The era of working on just this gene or that gene is over," he adds.

THE URCHIN-WIDE WEB

It was these fast-tracked methods of gene analysis that allowed biologists, led by Davidson and his Caltech colleagues, to map out almost all the switches and connections that control a sea-urchin embryo's gene regulatory network during the first 30 hours of its life, until it begins its gastrula stage. "We've been able to understand the gene regulatory network of the sea-urchin embryo more completely than other embryonic networks," Davidson says.

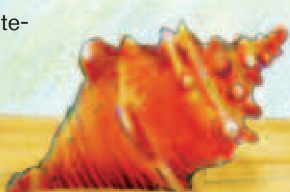
As part of building that map, senior research fellow Qiang Tu and former staff scientist Paola Oliveri (now at University College London), together with Davidson, were able to piece together the details of the part of the regulatory network responsible for generating the cells that build the biomineral rods that ultimately form the sea-urchin embryo's skeleton. By mapping this skeleton-forming network, Davidson notes, the researchers became the first to explain completely—in terms of the underlying DNA instructions—how genes interact to govern the development of a particular type of cell

in a developing animal embryo.

In an accompanying commentary to the paper, biologist and former Caltech professor Leroy Hood (BS '60, PhD '68) called the work a "tour de force."

"This paper will be the model for many more that will undoubtedly follow, transforming the landscape of developmental biology and ultimately elucidating the molecular systems that drive development," Hood wrote.

He was indeed prescient. Just last year, Davidson and senior research fellow Isabelle Peter published an analysis



of the 14-gene network responsible for the development of another type of embryonic cell—endoderm cells, which are the ones that eventually form the sea-urchin larva's gut. Because of this work, Davidson says, biologists now know more about how endoderm cells develop in the sea urchin than any other kind of cell.

What Peter and Davidson found was that gut-regulating genes begin expressing themselves in specific cells just a few hours after the egg is fertilized—well before the gut begins to take shape. In fact, it is becoming clear that an egg is created with some regulatory features that foreshadow its cellular destiny. Even though the egg is a single cell, its composition is not the same throughout; certain gene-regulatory proteins are more prevalent at one pole of the egg than another, for instance. As a result, when the fertilized egg divides, only some cells will contain those proteins. And if those proteins are the ones that, for instance, are needed to turn on the gut-forming genes, then only those cells will know to begin expressing the regulatory genes that will direct the program of gene expression that ultimately results in the formation of a gut tube in the embryo.

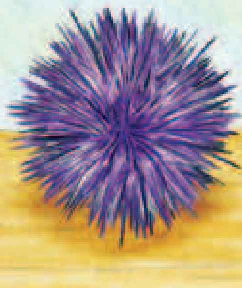
To get an even deeper understanding of their findings, Peter, Davidson, and postdoc Emmanuel Faure are working on a Boolean computer model to generate in the computer the outputs of the gene regulatory networks of endoderm and mesoderm cells, which respectively form muscles and parts of the immune system. The model is a series of if-then statements that compute the consequences of turning each gene on and off. With this computational tool in hand, the scientists can compare the model to a real embryo, hour by hour, seeing which genes in the network are being expressed, and which are being shut down. So far, Davidson says, the model is remarkably good at reproducing what their experiments have found in real sea urchins. The researchers can even do virtual experiments by seeing what happens when they tweak the model network. The model is so good that the results of those virtual experiments match the real ones, further demonstrating that the model represents a complete understanding of the network and, more significantly, that the network itself encapsulates almost the entire control system that determines what genes will be expressed, when, and where for this part of embryonic development.

Within a couple of years, Davidson says, biologists will have analyzed most of the sea-urchin embryo's genetic networks and will thoroughly understand the control system underlying its development. In working toward that goal, Stefan Materna (PhD '12), Caltech staff biologist Andy Ransick, senior research fellow Smadar Ben-Tabou de-Leon, and postdocs Enhu Li and Julius Barsi are probing the networks responsible for the rest of the embryo, which includes the cells that form the outer wall and its various structures—the mouth and parts of the neuronal system, for instance—and the cells that differentiate into the diverse kinds of mesoderm cells, including pigment and immune cells. Isabelle Peter and two graduate students, Miao Cui and Jon Valencia, are analyzing the later processes of gut development, in which the stomach, intestine, and foregut are formed. Senior research fellow Qiang Tu and Cameron have analyzed all the RNA that is produced every few hours during gene expression while the sea-urchin embryo develops. Meanwhile, members of the Davidson laboratory are constantly improving the technology for studying gene regulatory networks. For example, scientific research associate Jongmin Nam recently invented a way to speed up analysis of gene regulation more than 100-fold.

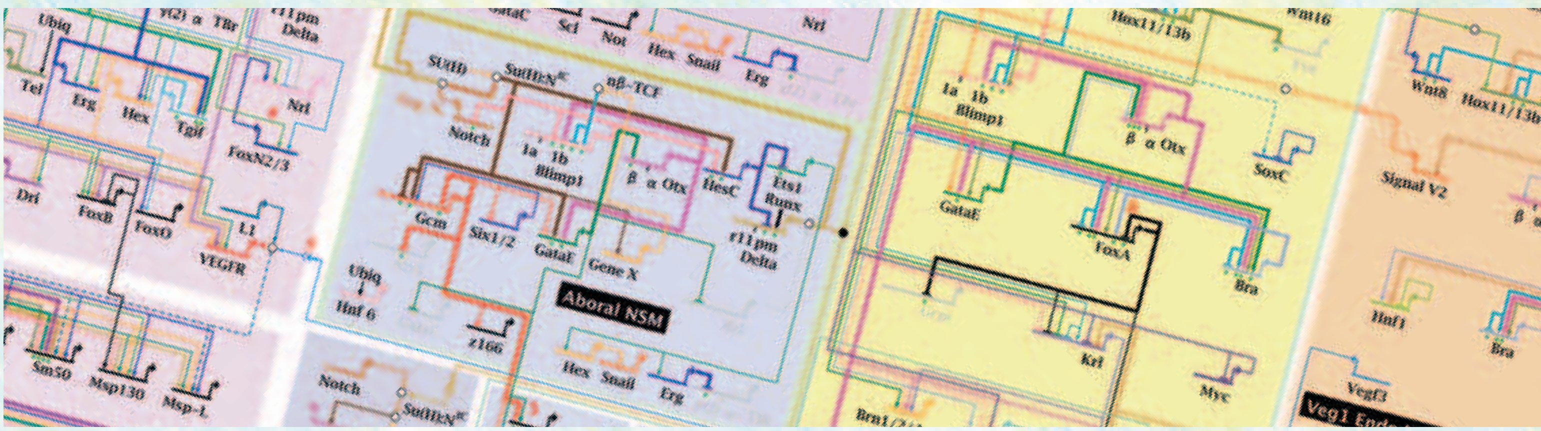
EVOLUTION AND MODULES

On paper, a sea urchin's regulatory network looks like an overly complicated subway map, with colorful lines and arrows that skitter across the page. And yet, Davidson says, these seemingly dense and intimidating sets of data are not as complex as they appear.

For one thing, the overarching networks are composed of smaller subcircuits—mini-networks, you might call them—with each involving just a few interacting genes. And they all consist of one of just a few dozen basic designs, each with a specific type of function. One such design, for example, might involve three genes in a positive feedback loop that stabilizes other genes downstream. Another subcircuit might result in boosting the expression of a particular gene in a specific type of



Below: Just a few of the myriad interactions among the regulatory genes that control a sea urchin's development are illustrated here. Scientists are discovering that these gene-regulatory networks have an inherent modular structure, which means the networks may actually be simpler than they appear.



cell while repressing it everywhere else.

In other words, these modules are like building blocks for a regulatory network, offering a powerful and simple way to make sense of hundreds of interacting genes. According to Davidson, there's evidence that similar module-based building blocks also exist in flies, worms, zebrafish, and frogs. This suggests that understanding the design of the subcircuits in sea urchins will help biologists understand other species—even if their embryonic development looks nothing like that of the sea urchin. "Understanding sea-urchin embryos blazes the trail for understanding other embryos," Davidson says.

They're also gaining some insight into the way in which one creature evolves into another—a process that would, by definition, rely on changes in the gene regulatory networks. In fact, says Davidson, evolution can be thought of as the assembling and reassembling of these network subcircuits. Over the course of millions of years, as mutations cause changes in regulatory genes, they may not only affect what an organism looks like, but what species it is. And so, by tracking how regulatory networks change from species to species, biologists can follow the precise mechanism of evolution—an achievement Charles Darwin could never have anticipated.

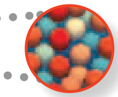
These changes can be directly observed by comparing different species. For example, scientific research associate Feng Gao is comparing a regulatory system found in both sea stars and sea urchins. Similarly, Eric Erkenbrack—a graduate student—is comparing the genomes and regulatory networks of the purple sea urchin with those of *Eucidaris tribuloides*, a cousin whose ancestors diverged from the purple sea urchin's about 275 million years ago. Although both species are sea urchins, much of their regulatory networks are wired differently, resulting in slightly contrasting developmental processes. For example, the two species form their larval skeletons from cells that have different embryological origins and behave in different ways.

To better understand such disparities, Erkenbrack is now trying to insert the set of regulatory genes responsible for the purple sea urchin's skeleton into *E. tribuloides*. The goal is to reprogram *E. tribuloides* to grow a skeleton just the way its purple relative does. The researchers call this synthetic experimental evolution. And if it works, it will also confirm that the genes the researchers have identified as the purple urchin's skeleton builders really *are* behind the differences in the way these two species build their skeletons.

"With all these advances, it's now feasible to think about understanding the whole genome," Cameron says. "It was great to be able to describe how one gene interacts with another gene. But the whole thing? Think about that. That's pretty cool." E&S

Eric Davidson is the Norman Chandler Professor of Cell Biology. Andrew Cameron is a senior research associate in biology. This research was supported by the National Institute for Child Health and Human Development, the National Institute of General Medical Sciences, the National Center for Research Resources and the Office of Research Infrastructure Programs of the National Institutes of Health, the National Science Foundation, the Lucille P. Markey Charitable Trust, the Norman Chandler Professorship in Cell Biology, the Camilla Chandler Frost Fellowship, the Beckman Institute, and the Baylor College of Medicine Human Genome Sequencing Center.

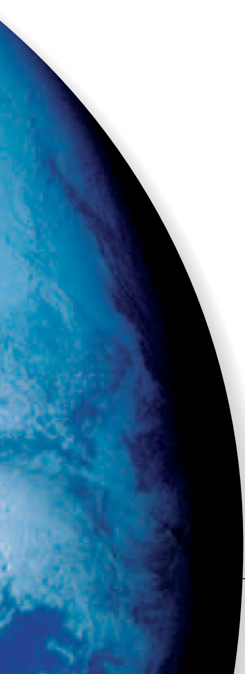
BIG SMALL THINGS

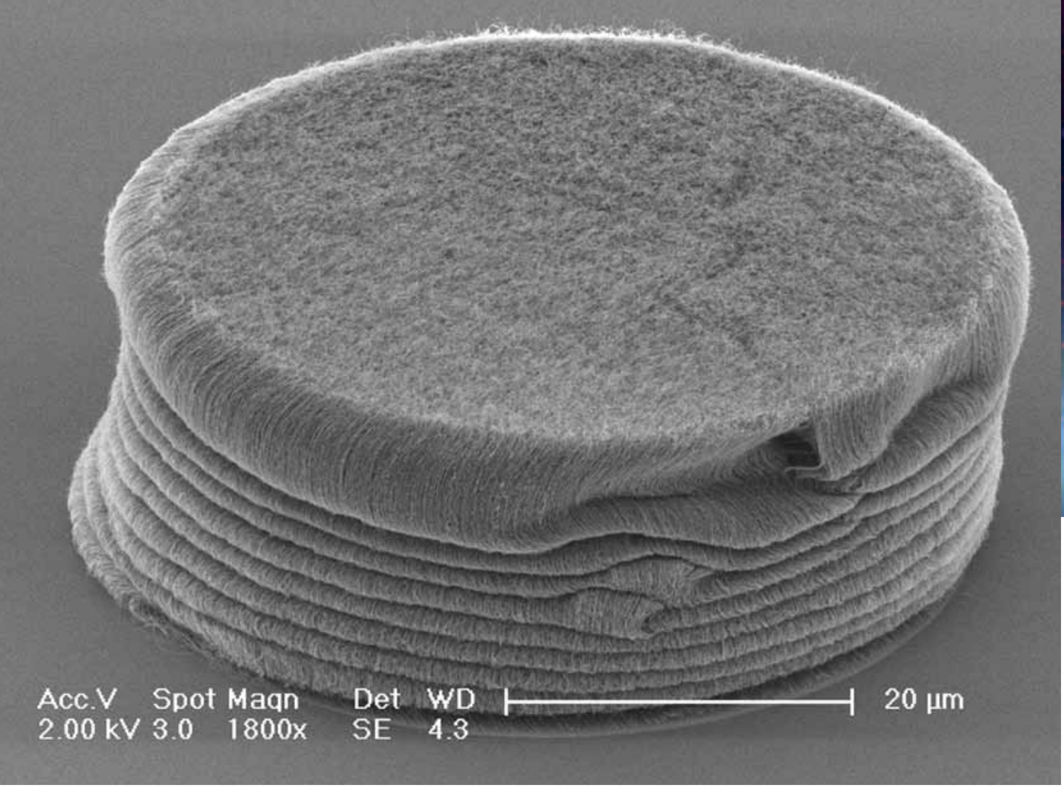


HAPPENING HERE

By Kimm Fesenmaier

As scientists extend the limits of our knowledge of the universe, we ponder the limitless possibilities for discovery. But there's another, more subtle frontier: It's the science of materials—the transformation of the everyday into the truly extraordinary—and it's right at our fingertips. It's just *really, really* small.





Left: This micropillar, made up of millions of carbon nanotubes, has been compressed by a nanoindenter in the Greer lab. Its smooshed profile reveals localized buckles in the structure.

More than 50 years ago Richard Feynman posited in these very pages that "when we have some control of the arrangement of things on a small scale, we will get an enormously greater range of possible properties that substances can have." Researchers on campus are now gaining such control, which will lead to materials that are stronger, lighter, tougher . . . better.

Think of it as modern-day alchemy—transforming existing matter into new materials by taking advantage of what happens at the micro- and nanoscales, where matter behaves in strange and wonderful ways. "We have to shift our way of thinking about creating new materials toward not being slaves to processing anymore," says materials scientist Julia R. Greer. In today's world, you start with an atomic structure and a processing route, which then dictates the properties that the end product will have. So far, the design process has not been used the other way around.

Greer dreams of the day when she'll be able to type into a computer, "I need something lightweight like an aerogel, that won't corrode and will be as strong as steel," and have it tell her exactly which raw materials to use and how to structure them into a bulk-scale material with those properties. Creating such a computer model, she says, is "the grand challenge in materials sciences."

Part of the reason this model doesn't already exist is that we don't know how to incorporate the vast range of different material scales—from atoms to nanometers to microns to the macro-level—nor how to account for the properties at each of these levels. In bulk materials—those at scales we deal with in everyday life—certain sets of properties tend to couple together. Strong materials tend to be heavy; bendy, or ductile, components tend to be weak. But materials that are really, really strong and extremely light? Or strong and tough? Those are lacking.

Things behave differently at the nanoscale, however. Greer has shown that, when reduced to the nanometer scale, a single crystal of gold becomes nearly as strong as steel, even though bulk gold is soft and malleable. Such "size effects" open up a grab bag of possibilities, but in order to be able to pick the right properties out of the bag, we need to learn a lot more about where they come from and—perhaps most importantly—how to build bulk materials with those same properties.

The tool of choice for measuring mechanical properties at these small scales is the nanoindenter, a computer-controlled, spring-loaded shaft equipped with a diamond tip at the end, allowing it to probe tiny samples, sometimes smashing them to smithereens, all in the name of science. By exerting a precisely calibrated force, scientists can measure how much a sample deforms, how much energy it can absorb, and where its breaking point is.

A standard nanoindenter usually comes equipped with a vertically oriented optical microscope, which allows researchers to see relatively large structures, but which cannot distinguish features at the nanometer scale. It also lacks the ability to grab samples from above to test their breaking strengths or watch them deform. In order to overcome these limitations, Greer's lab built a souped-up version called the SEMentor (pronounced "cementor"), which is composed of a nanoindenter-like module inside a scanning electron microscope (SEM). The SEMentor allows researchers to grab the samples and watch deformation in real time.

"When you only have numerical data, the best you can do is hypothesize about what probably happened and then do a bunch of other indirect measurements to confirm or refute your hypothesis," Greer says. "But now we can say, 'Here's the data, and this is what really happened.'"

Equipping the SEMentor with custom-built grippers gives it the ability to not only poke or crush a sample, but also to stretch it. The Greer group's members have been stretching a

wide range of materials: small-scale samples made of metals, composites, carbon nanotubes, and metallic glasses, to name a few. Bulk metallic glasses, or metallic alloys that lack the crystalline structure of traditional metals, are normally quite brittle, but Dongchan Jang, a postdoc in Greer's group, found that tiny pillars of metallic glass that are 100 nanometers in diameter can stretch by about 25 percent—23 percent more than the bulk material can—without breaking.

This is important because a metallic glass's irregular jumble of atoms inevitably contains stronger regions and weaker ones. If there are enough weak regions in a narrow plane, a sufficiently hard tug will coalesce them into a so-called shear band, which then rips through the sample—a catastrophic failure.

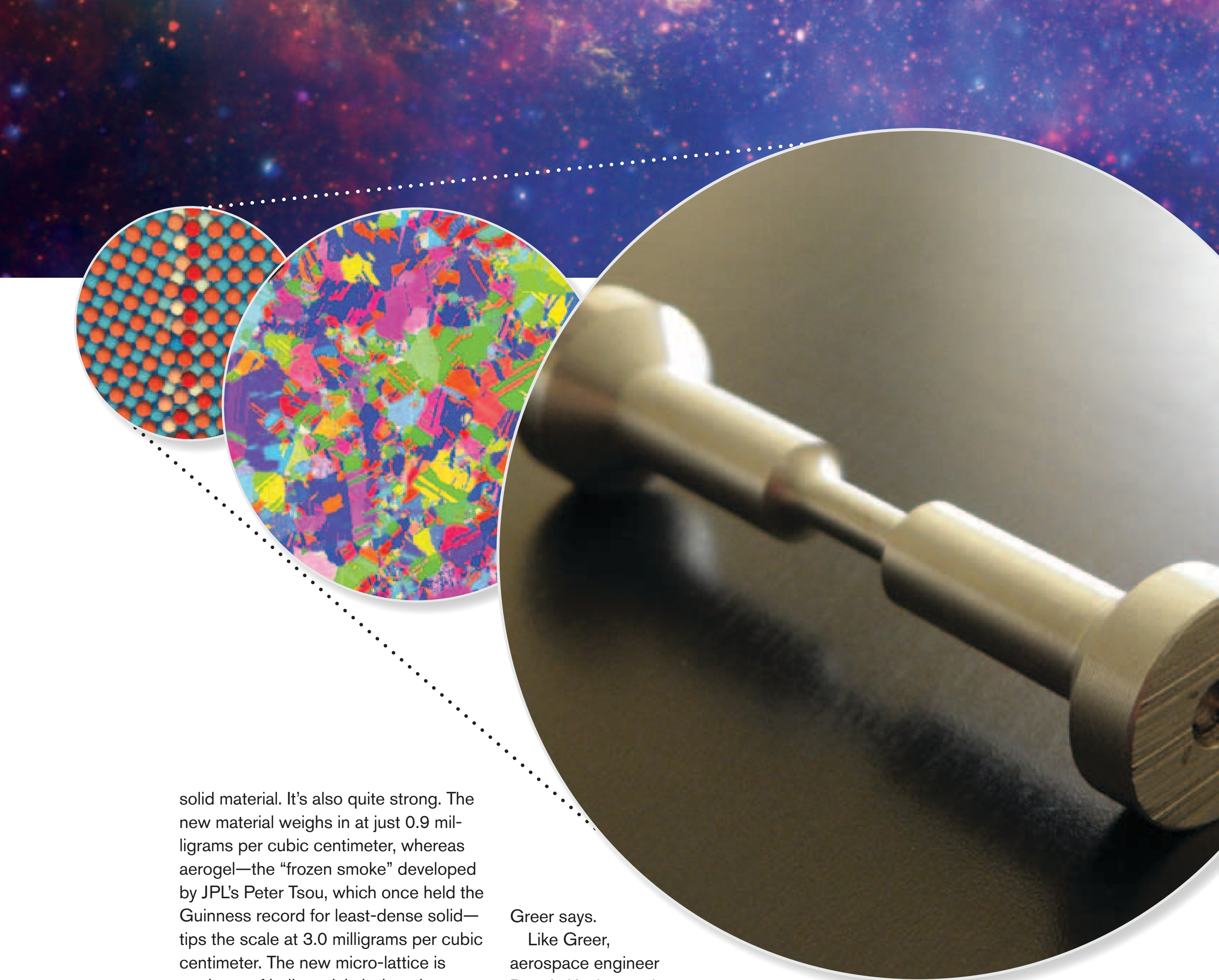
This is where the size effect comes in: nanostructures have a lot more surface than interior. "In a small structure, you have surfaces everywhere. You don't have a constant supply of mobile crystal defects, or dislocations, so the crystals have to create new ones, which takes a lot of energy," Greer says. "Even the number of atoms is limited. So you're in this starved state. It's that starvation of defects and its consequences for the atomic features that give rise to interesting properties."

But you can't build an airplane or even a coffee mug out of nanopillars. To bring these size effects to a larger scale, Greer's lab is creating what she calls hierarchically structured materials. A hierarchical material consists of tiny structural elements whose properties bring certain advantages to the material; those elements are then aggregated into larger structural elements that preserve the advantages. The larger elements can then be aggregated themselves, leading to a whole new set of beneficial properties, and so on.

In this way, Greer and her colleagues are taking a page from Mother Nature's book. Nacre, the iridescent lining of many seashells, is a hierarchical material. Also known as mother-of-pearl, it is 95 percent aragonite, by volume, but 3,000 times tougher than nacre alone. The reason: the densely packed, microns-long tablets of aragonite are stacked like bricks, with nanometers-thick layers of proteins and chitin acting as mortar. When a crack gets started, the brick-like structure prevents the flaw from propagating. It might extend through one brittle aragonite tablet, but the surrounding organic layer will keep it from destroying the entire shell. Also, under stress—from the pounding surf, for example—the organic mortar gives, allowing the tablets to slide past one another and distributing the power of the blow.

Inspired by this hierarchical notion, Greer's lab recently collaborated with UC Irvine and HRL Laboratories, LLC, in Malibu, to develop a "micro-lattice" that now ranks as the world's lightest

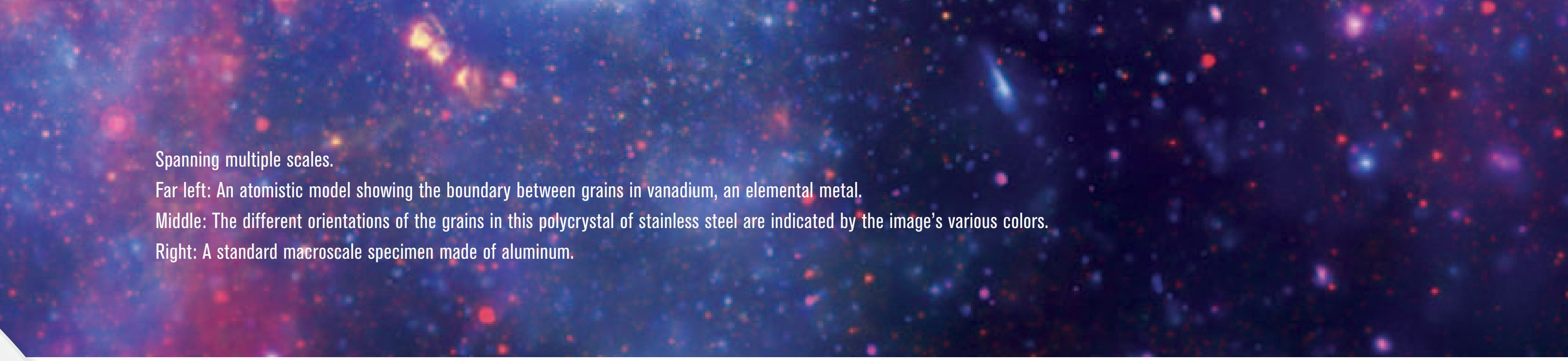
This hierarchically structured microlattice, which Greer helped develop, is now considered the world's lightest solid material.



solid material. It's also quite strong. The new material weighs in at just 0.9 milligrams per cubic centimeter, whereas aerogel—the "frozen smoke" developed by JPL's Peter Tsou, which once held the Guinness record for least-dense solid—tips the scale at 3.0 milligrams per cubic centimeter. The new micro-lattice is made up of hollow nickel-phosphorous tubes, connected at angles to form repeating, asterisk-like unit cells, with open voids making up 99.99 percent of the material. Each tube's walls are just a few hundred nanometers thick, exploiting a size effect to withstand deformation. By building the micro-lattices with tubes that are microns in diameter and millimeters in length, the team found that the material could rebound from a strain that compressed it by as much as 50 percent, making it an excellent energy absorber.

"This is a new era of materials science where properties are determined by both microstructure and architecture," Greer says.

Like Greer, aerospace engineer Dennis Kochmann is interested in being able to "design material behavior by demand," as he puts it. Kochmann is developing models and computer simulations to investigate the physical behavior of metals, and those models will span multiple scales—from the macroscopic level, which can be seen with the naked eye, all the way down to the level of individual atoms. His work originally started at the macroscopic level, with the modeling of the physical behavior of entire objects or devices made of conventional polycrystalline metals. But since coming to Caltech in the fall of 2010, he has adopted and advanced some of the unique techniques developed by Hayman Professor of Aeronautics and Mechanical Engineering Michael Ortiz for bridging scales down to the level of individual atoms. As a result, Kochmann's work now includes the opposite end of the spectrum—studying the discrete lattice of atoms that make up metals and looking in particular at the defects, such as dislocations and vacancies, within those lattices. The outputs of these atomistic simulations will inform the model at higher levels, where, for example, the



Spanning multiple scales.
Far left: An atomistic model showing the boundary between grains in vanadium, an elemental metal.
Middle: The different orientations of the grains in this polycrystal of stainless steel are indicated by the image's various colors.
Right: A standard macroscale specimen made of aluminum.

different orientations of grains—groupings of lattices—and the boundaries between them also affect a material's properties.

"It's very important to study what is going on at these lower scales: How do these defects interact? What do they do? What is their energy? How do they move?" Kochmann says. "We try to model how these defects interact to give rise to the very specific behaviors we observe at the macroscale."

And understanding leads to prediction. "If you design a completely new structure or aircraft, let's say, you want to be able to predict how much load it will be able to carry, when it will break, and so forth," Kochmann says. "Once we understand the connection between microscale and macroscale, we should be able to use that in order to design new materials with the beneficial properties we want."

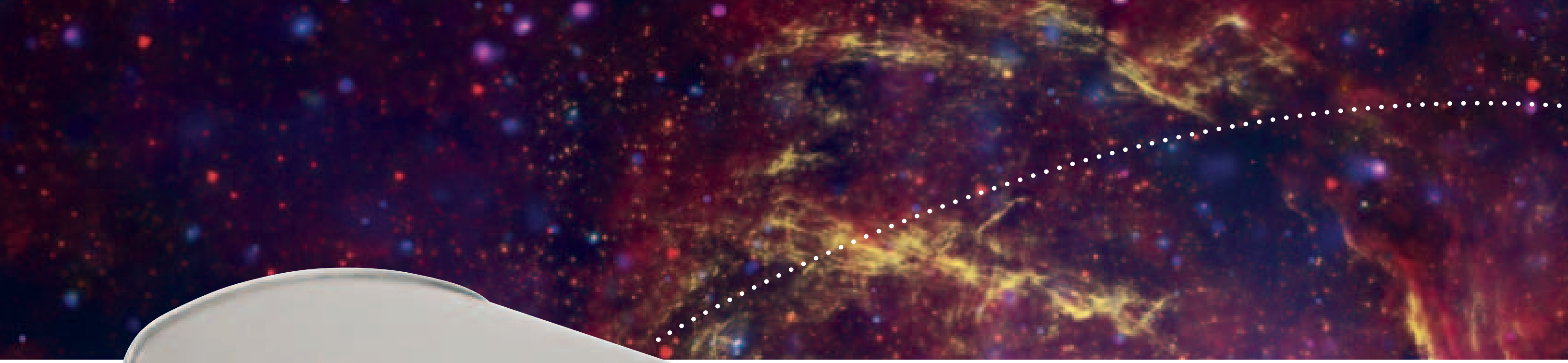
Kochmann isn't just interested in modeling, though. As a graduate student in Roderic Lakes's lab at the University of Wisconsin–Madison, he helped develop a composite material with an unusual combination of properties—extremely high stiffness *and* high damping, which is the ability to absorb energy. This combo would be useful for such things as an airplane wing that doesn't bend but absorbs vibrations, or an armor plate that soaks up the energy of a projectile. The key to this material is that it's tunable by temperature: near 120 degrees Celsius, the material becomes extremely stiff and highly damping; much above or below that temperature, the material is less stiff and only moderately damping.

"It's very important to study what is going on at these lower scales: How do these defects interact? What do they do? What is their energy? How do they move?"

Now that he's at Caltech, Kochmann plans to make similar composites that transform through other mechanisms. It might be possible, for example, to use materials that change under electric fields, like certain piezomaterials. "The idea is to eventually have a material that changes its properties at the push of a button," Kochmann says.

Meanwhile, researchers elsewhere on campus are pursuing materials that would be able to conduct electricity well while protecting against heat conduction. Substances with high electron mobility, such as metals, conduct both electricity and heat; insulating glasses, in which the electrons are firmly bound to their atoms, conduct neither. But a semiconductor rod that is a thermal insulator *and* an electrical conductor can convert heat into electricity; heating the rod on one end causes charge carriers—electrons and "holes" (which carry a positive charge)—to migrate toward the cool side, creating an electrical flow.

Such thermoelectric generators are nothing new. NASA used them in the Apollo program and on the Viking landers, and such generators are keeping the twin Voyager spacecraft fueled on their epic journey. The generators are also headed to Mars, where they will power the *Curiosity* rover. But earthbound thermoelectrics are returning to the limelight these days as well, because they have the



potential to turn otherwise wasted heat, such as that in car exhaust or factory emissions, into usable energy.

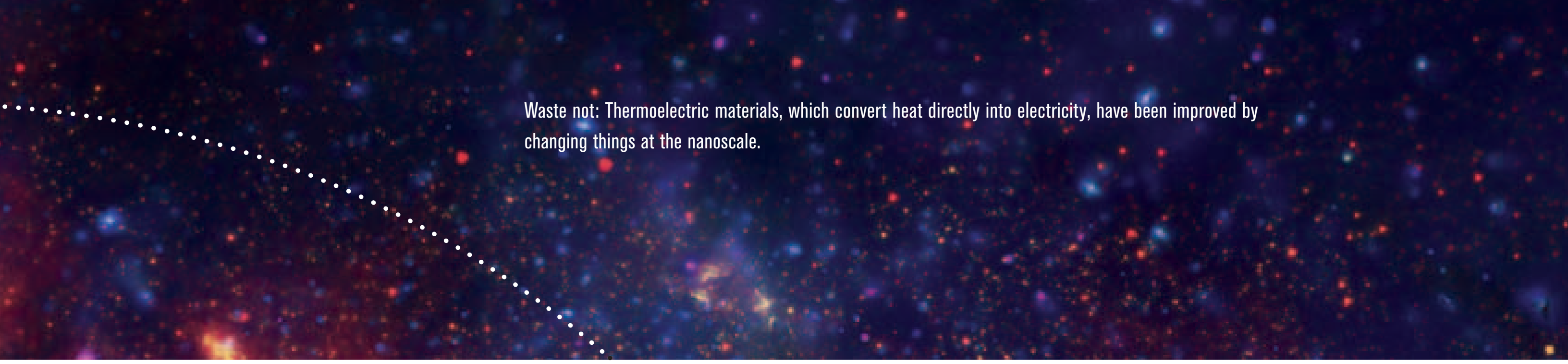
In the last year or so, materials scientist Jeff Snyder has made major advances in the "recipe" for lead-telluride-based thermoelectrics—descendents of the type used in the Apollo instrument packages. He has significantly improved their electronic properties, and, most recently, has come back to the idea of including nanostructures in them to decrease thermal conductivity.

Snyder's lab first started experimenting with this concept of nanoinclusion nearly a decade ago. One way to produce such nanoinclusions is to add a secondary material such as silver telluride into the melted original semiconductor and then carefully cool the mixture. The idea is that if the particles are the right size, they will disrupt the motion of the phonons—heat-carrying packets of thermal vibrations akin to photons, which are packets of light—without disrupting the material's electrical conductivity.

But after making some really complicated materials along these lines, the researchers identified a problem—they couldn't say for certain that the improvements they were seeing were purely because of the nanoinclusions. So they stepped back and started working with simpler materials. "What we discovered was that everybody, including ourselves, was comparing our nanostructured materials against reports from 1960 that relied on an inaccurate thermal conductivity measurement," Snyder says. When they went back to the lab, they found that the measurement for lead telluride was off by about 30 percent.

Once Snyder's team pinned down this pervasive error, they saw that there was room for improvement with lead telluride. The measure of efficiency in thermoelectrics is a dimensionless unit called the figure of merit, zT, and for nearly 50 years, the highest zT of lead-telluride-based thermoelectrics was thought to be 0.8. But by carefully selecting which elements to add to the lead telluride, Snyder's lab improved the electronic properties to achieve a peak zT of nearly 1.8—an enormous increase. Most recently, the team has shown

> It's still early days when it comes to investigating the bizarre properties that can arise at the smallest of scales.



Waste not: Thermoelectric materials, which convert heat directly into electricity, have been improved by changing things at the nanoscale.

that nanoinclusions can improve a material even further by improving its average *zT*. For a thermoelectric to be useful in the real world, it needs to operate at a range of temperatures—in a car's muffler, for example, it would need to work anywhere between 50°C and 600°C. That means the average *zT*—the efficiency of the thermoelectric—needs to be high across all those temperatures. "So," says Snyder, "even though the exciting papers are the ones where the peak *zT* is very high, the important ones are really the ones where the average *zT* is boosted."

To make his thermoelectrics better, Snyder realized, it is the spacing between the particles that really matters. According to theory, about 20 percent of phonons in lead telluride have a mean free path—the distance they can travel without being disrupted—of longer than 100 nanometers. So by spacing nanoinclusions 100 nanometers apart, the team can increase scattering and reduce the material's overall thermal conductivity. Thus, while many teams have focused on making ultrasmall nanoinclusions—on the order of five or 10 nanometers in diameter—Snyder's group uses particles 50 nanometers in length, or even larger. Indeed, Snyder sometimes jokes that his is "the *large* nanoparticle research group."

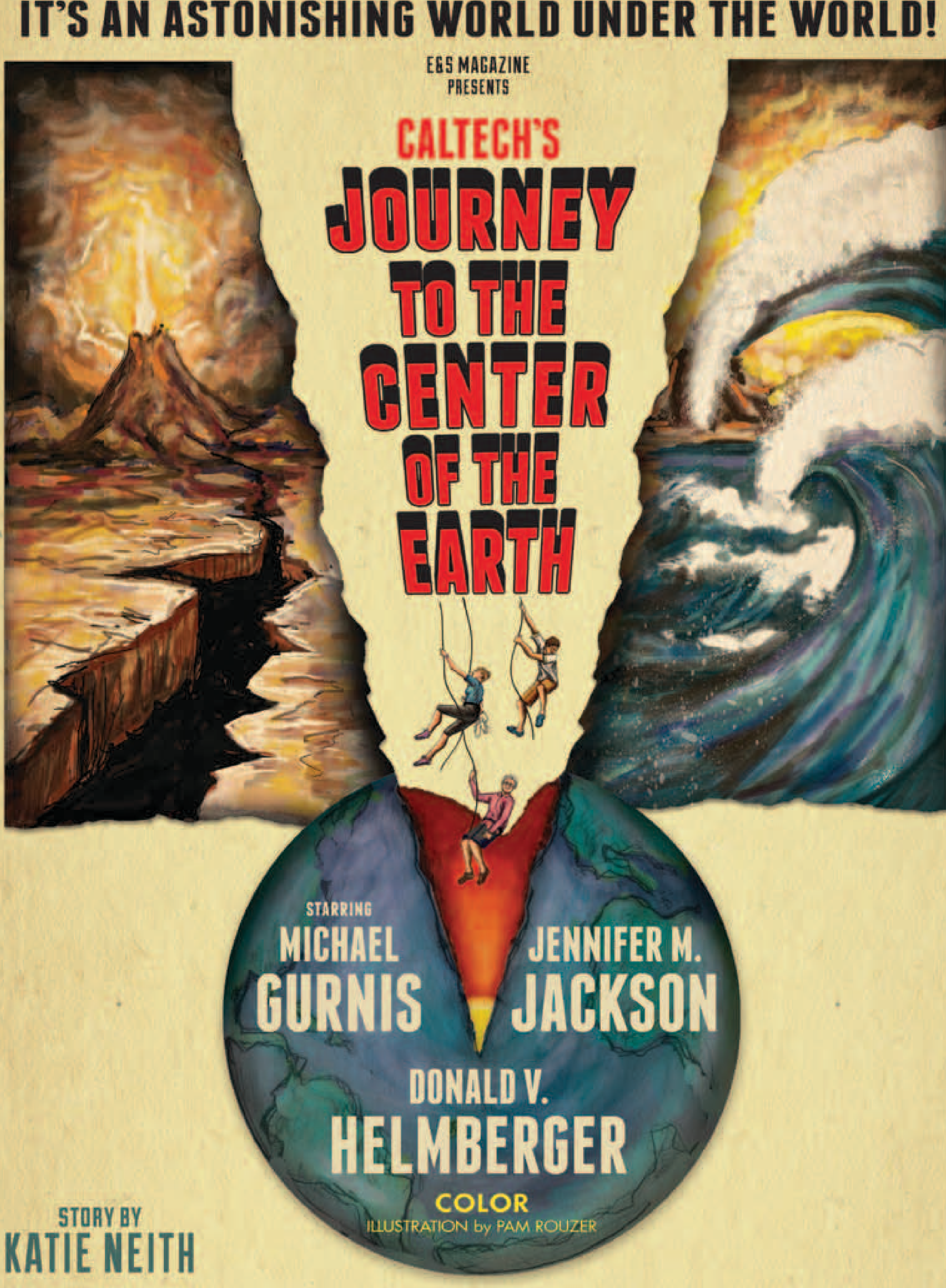
As all three of these scientists point out, it's still the early days when it comes to investigating the bizarre properties that can arise at the smallest of scales. And we're only just beginning to take advantage of the nanorealm to conjure up materials never before considered.

Still, the situation looks quite different today than it did in 1959, when Feynman told *E&S*, "We have been content to dig in the ground to find minerals." These days, instead, we're burrowing down to the nanoscale, and finding new possibilities. E&S

Julia Greer is an assistant professor of materials science and mechanics. *Her work on nanopillars and with the SEMentor is funded by the National Science Foundation and the Office of Naval Research, and utilizes the fabrication and characterization facilities of the Kavli Nanoscience Institute at Caltech.*

Dennis Kochmann is an assistant professor of aerospace. He joined the Caltech faculty in 2011. *His research is supported by the Haythornthwaite Foundation, as well as by Caltech.*

Jeff Snyder is a faculty associate in applied physics and materials science. *His thermoelectrics research is supported by NASA-JPL, the DARPA Nano Materials program, and the Chinese Academy of Sciences.*


IT'S AN ASTONISHING WORLD UNDER THE WORLD!
E&S MAGAZINE PRESENTS
CALTECH'S
JOURNEY TO THE CENTER OF THE EARTH
STARRING
MICHAEL GURNIS
JENNIFER M. JACKSON
DONALD V. HELMBERGER
COLOR
ILLUSTRATION by PAM ROUZER
STORY BY
KATIE NEITH

In Jules Verne's 1864 sci-fi tale, *A Journey to the Center of the Earth*, a group of explorers access the deepest parts of our planet through a volcano to discover a world of giant mushrooms, huge geysers, and violent prehistoric creatures, among other oddities. The theory that people could travel miles below the earth has since been refuted, along with many of the other ideas that Verne posed in his book. And yet, we still don't know the exact composition and structure of the earth's interior. Which is why, like Verne's trio of adventurers, three researchers in the Seismological Laboratory in Caltech's Division of Geological and Planetary Sciences are combining their talents to build a better picture of what lies deep beneath the earth's surface.

Our planet can be roughly divided into five parts: the crust, the upper mantle, the lower mantle, the outer core, and the inner core. If it *was* humanly possible to take a trip to the core, one would first have to get through the lithosphere—which consists of the rigid, rocky crust and the uppermost part of the mantle, which is broken into tectonic plates. Under the lithosphere lies a weaker and hotter part of the upper mantle, which likely resembles an ocean of rocks in some places, particularly where it bubbles up to feed volcanoes. Next, our intrepid travelers would find the lower mantle, a layer of highly viscous rock—mostly solid, but with the ability to flow over long periods of time—that extends down to a depth of nearly 2,900 kilometers. There they would hit the outer core, a layer of molten nickel-iron alloy over 2,200 kilometers thick. The final stop, the inner core, is thought to be a solid ball of similar material, with a temperature comparable to that of our sun's surface, at approximately 5,500 degrees Celsius.

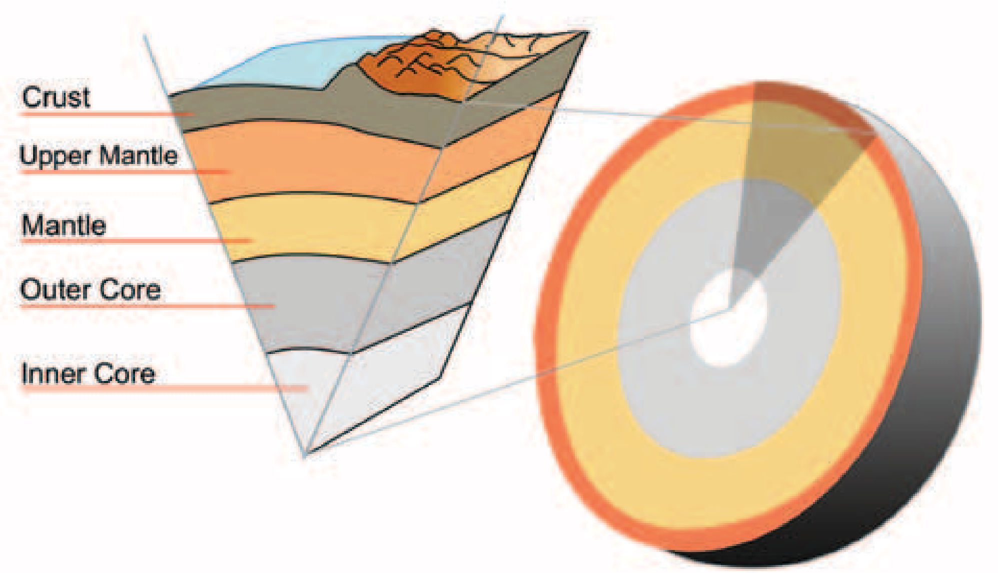
These layers are in constant motion. The earth's magnetic field originates in the outer core and is generated by convection, as the liquid metal roils like soup in a pot on a hot stove. Similarly, convection in the mantle carries heat from the interior to the surface, with the tectonic plates forming the upper part of the convection cells. "The earth is an incredible, dynamic system," says geophysicist Mike Gurnis, whose specialty is computational geodynamics. "But we cannot go deep inside the planet directly with a thermometer; nor can we sample the composition of the rocks directly. So we're working to take all the data we have—from a variety of sources—and integrate them into a comprehensive model. Some of this data is taken from the earth's surface, including information about evolution deciphered from rocks, while remote-sensing data tells us about the physical state of the deep interior."

By *we*, he means himself, seismologist Don Helmberger, and mineral physicist Jennifer Jackson.

"We use different methods and different data, but we're trying to exploit their complementary nature," says Gurnis. "Between Don, Jennifer, and myself, we have a triangle of different methodologies, but seismology is the most direct way we're making observations."

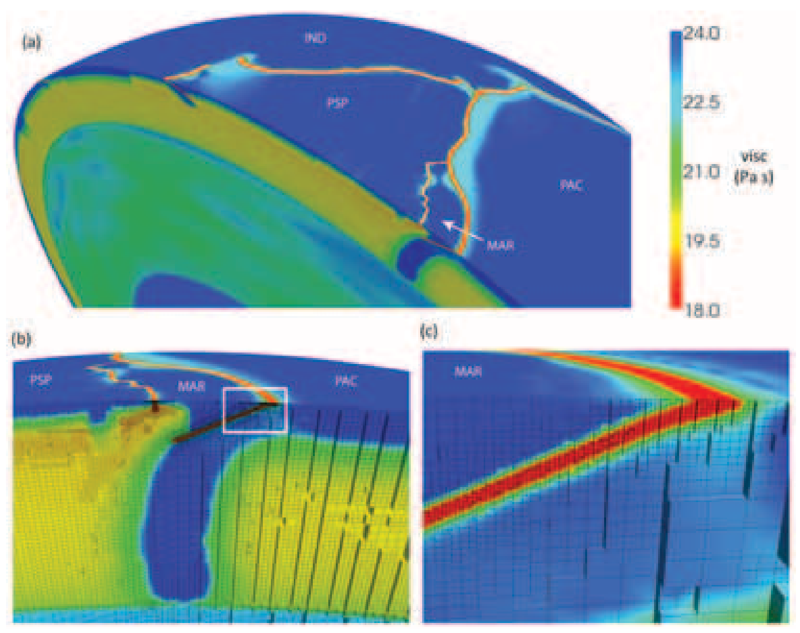
Seismology is a good place to start, partly because it's been around a bit longer than the other disciplines, says Helmberger, who has been a faculty member at Caltech since 1970, and who devised the first synthetic seismogram three years before his arrival, during his grad studies at UC San Diego.

Synthetic seismograms are models that use wave-propagation data to help model the earth's structure and movement. Helmberger first used the method to investigate the crust-mantle transition in the Bering Sea for his



This diagram shows the five basic layers of the earth, from the outer crust—on which we live—to the innermost layer of the core. The distance from our planet's surface to the middle of its inner core has been determined to be approximately 6,300 kilometers at the equator.

(a) A multiscale global model from Mike Gurnis's lab shows an area of the western Pacific. By "zooming in" on the subducted slab south of Japan in the Marianas Islands (b), the model shows the dynamic weakening of the Pacific Plate. A further zoom in on the fault between the two plates (c) shows the system of grids used to apply computer algorithms in order to learn more about individual fault zones.



PhD thesis in 1967. When he started working in seismology, researchers in the field were using small explosions to measure seismic waves. The advantage of this, of course, was that they could control when and where the explosives went off. A network of sensors called geophones would monitor the resulting seismic waves, which could then be analyzed mathematically to build up a picture of how the shock waves traveled through the layers below.

"The trouble is that explosions are expensive and disruptive, and you can't put them in many places," Helmberger notes. "So we started treating earthquakes as explosions, in the sense that you could determine all their properties."

It's been 40 years since he made his first model of an earthquake, a research move inspired by the 6.6 Sylmar quake that shook Southern California in February 1971. Since then, seismological modeling has become an integral part of geophysics research well beyond temblor studies. Helmberger in particular has used seismic modeling to map the core-mantle boundary and define some characteristics of superplumes, giant upwellings of the mantle that rise all the way up to the lithosphere to feed volcanoes. Since 1997, he and Gurnis have combined their different methods of modeling in the hopes of creating a clearer picture of the earth's interior.

Gurnis, for his part, uses computational geodynamics to interpret seismological observations made on local, regional, and global scales. In fact, he was part of a breakthrough study published in 2010 that modeled, simultaneously, the earth's mantle flow, large-scale tectonic motions, and the behavior of individual fault zones using computer algorithms.

"This was the first time that researchers were able to get the physics of the plate motions into the models correctly," says Gurnis of the research, done in collaboration with scientists at the University of Texas at Austin and published in the journal *Science*. "We were able to resolve the structure around the giant faults while zooming in to areas where the forces driving and resisting plate motions are balanced. This allows us to predict the large-scale motions of the planet, as well as some of the details."

He says his research has a dual focus of trying to understand the physics of the interior by including the history of the earth in the discussion, while at the same time attempting to provide a deeper physical understanding of why the earth's surface evolved the way it did.

"When you look at structures inside the planet, there is a clear pattern that's related to present-day plate tectonics on the surface and the evolution of plate tectonics," explains Gurnis. "So we create models of the earth that are intimately connected to the geological evolution of the surface. I'm filling in this gap between Don and Jennifer and creating structural models based upon the history of the earth itself."

The seismic waves passing through Gurnis's models change course or velocity as they pass through regions of different temperatures, densities, and chemical compositions. Figuring out how those properties change the speed of seismic waves is mineral physicist Jennifer Jackson's province.

"We focus on trying to understand what minerals are found deep inside the earth," says Jackson, who joined Caltech in 2007. "Those minerals—or iron alloys if we're talking about the earth's core—dictate how the whole earth behaves."

Her research group looks at how earth materials behave under the extreme temperatures and pressures of the earth's interior by recreating those conditions in a diamond anvil cell. These compact devices—some are small enough to carry in your pocket—squeeze sand-grain-sized samples between two diamonds to create pressures up to 3.6 million times what we feel at the surface. That's a lot of work for a tiny, precious gem.

The group prepares its cells at Caltech and takes them to an X-ray source at the Argonne National Laboratory in Chicago—one of only three X-ray facilities in the world powerful enough to do this kind of study. While the diamonds squeeze the sample and a laser heats it up, the X-rays interact with lattice vibrations in the materials—essentially creating ripples of distortion in the crystal structure that pass through the sample.

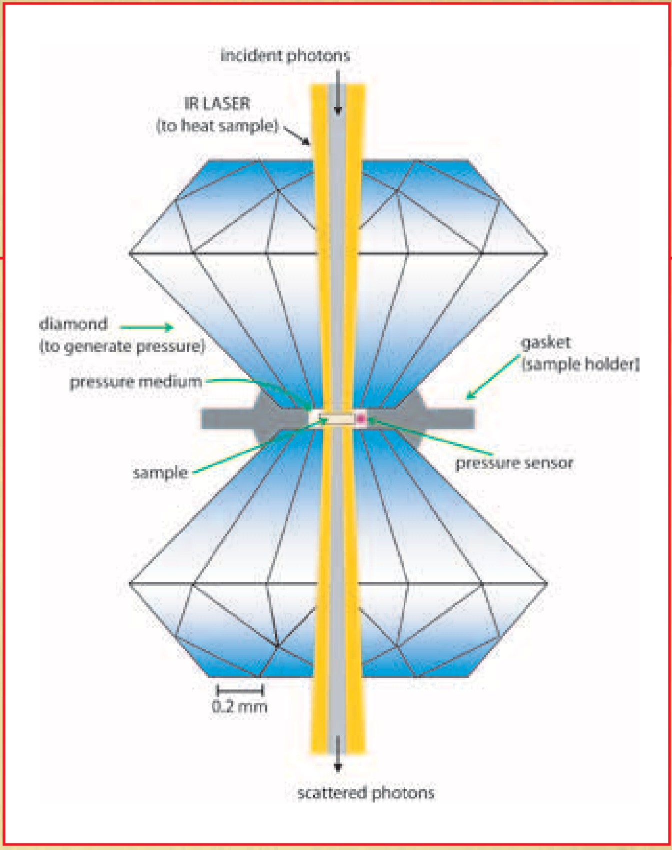
"By measuring these vibrational properties, we can understand what these minerals and iron alloys look like to seismic waves that pass through them," says Jackson. "And by recreating the conditions we expect them to be at, we arrive at a closer understanding of what's really down there."

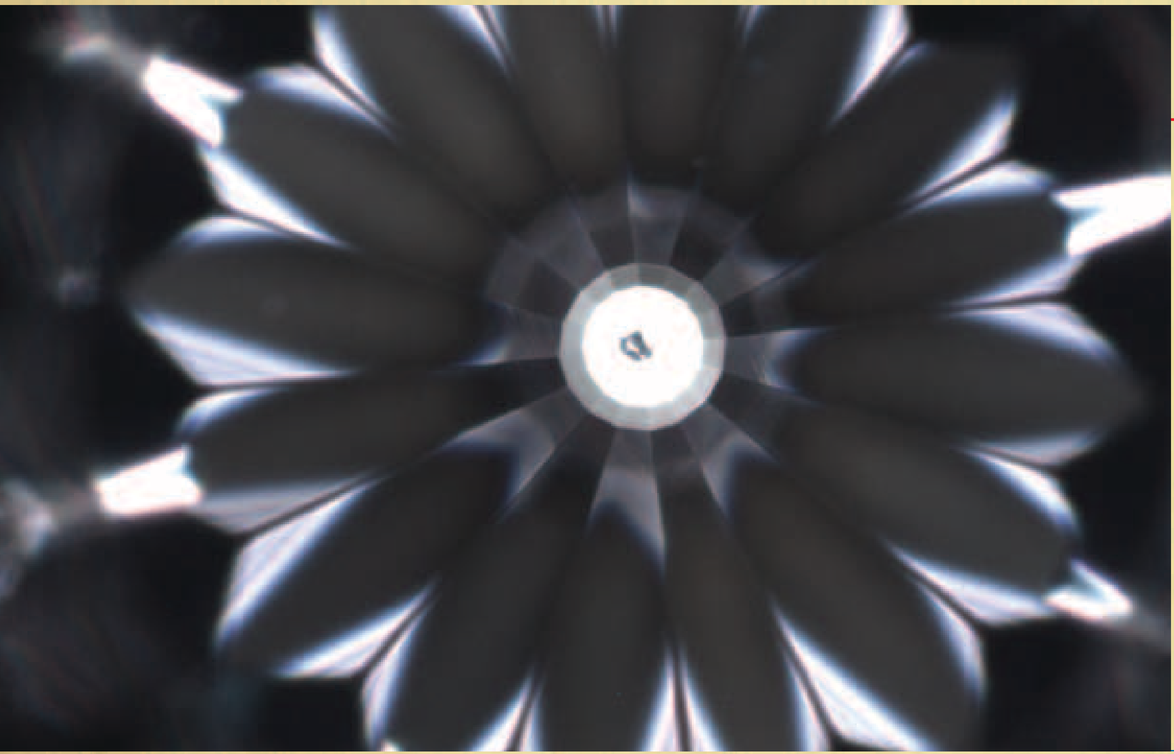
Similar measurements have been done at surface conditions, but Jackson notes that once you compress a material, it's very difficult to predict its behavior. The only way to really know how a mineral will behave inside our planet is to measure it under deep-earth conditions.

"When we do high-pressure, high-temperature experiments, we discover properties we would not have imagined," says Jackson. "It's not as if we are finding unphysical behaviors—like defying the law of gravity or anything—but our experiments allow us to open our minds up to different models of the earth's interior. By different models, I mean what types of landscapes are possible down there, which can indicate how the earth's interior has evolved."

Recently, she, Gurnis, and Helmberger have been focusing on the core-mantle boundary, home to ultralow velocity zones, or ULVZs. Discovered by Helmberger's group in the mid-'90s, ULVZs are areas where seismic waves travel very, very slowly.

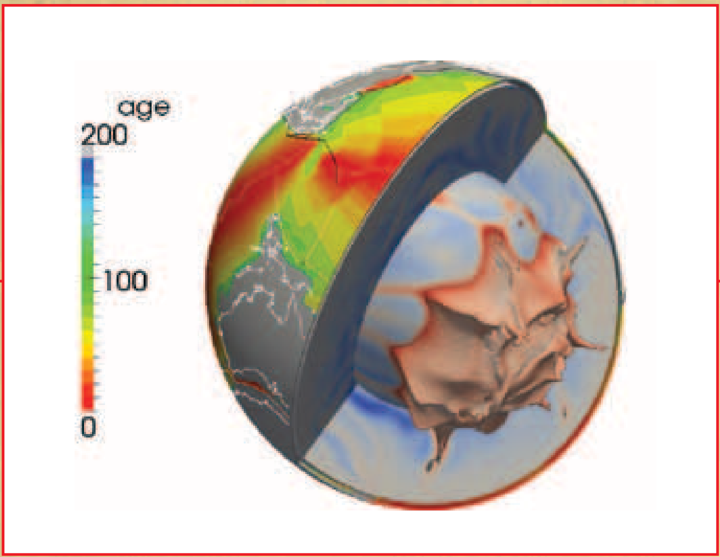
At the core-mantle boundary, which is roughly halfway to the center of the earth, the churning liquid-iron alloy that is carrying heat away from the earth's outer core meets the insulating silicate





Top: A schematic cross section of the diamond anvil cell used by Jennifer Jackson. Two diamonds (in blue) squeeze a tiny, deep-earth sample while an infrared (IR) laser heats it and X-rays probe the atomic vibrations. By learning more about the vibrational properties of compressed samples, the team can study how seismic waves will behave when passing through.

Left: An overhead image of a beveled diamond anvil with a single crystal of olivine in the center. This tiny piece of the earth's mantle is ready to be outfitted with a sample chamber so that it can be pressurized in the diamond anvil cell, as shown above.



A dynamic earth model reveals both the tectonic plates at the surface, and the structure of the deep mantle. This snapshot is of the late Cretaceous period (about 77 million years ago), when Australia was still connected to Antarctica. The large pink surface seen at the core-mantle boundary is a mass of dense material responsible for the plumes of mantle that appear in the Pacific Ocean.

rocks of the mantle. The ULVZs lie just above this boundary, at the bottom of the mantle, and the traditional idea was that they were regions of molten rock in an otherwise solid zone.

"We're finding that the core-mantle boundary is complicated, like the surface of the earth, and these patches of ULVZs—which we've been able to image seismically with Don Helmberger's group and model dynamically with Mike Gurnis's group—appear to have a more solid-like behavior," Jackson says.

"This was a beautiful example where we combined our dynamic models, we created a theory, and we used our laboratory results to predict the seismic characteristics of the ULVZs," says Gurnis.

Based on these models, theories, and lab results, the researchers now believe that many ULVZs are solid, heavy layers of iron-rich material, but also that those layers can bulge up into the lower mantle, thanks to the hotter outer core material lying beneath them.

"We have all this energy coming out of the core, so the ULVZs are going to get hot. As they heat up, it's likely that their density will drop, causing them to bulge," says Helmberger. "We believe these bulges look like big rolling hills, and think that we have detected these things at the core-mantle boundary. Unfortunately, it's kind of hard for us to drill a hole down there and say 'here it is—look at it.' But we're pursuing this idea with a lot of enthusiasm."

The three research groups are also working together to build better models of superplumes, which they believe are giant structures in the deep interior beneath Africa and the Pacific Ocean that are full of materials hotter than their surroundings. Learning how this material convects and how these deep structures behave can help in the understanding of large-volume eruptions that have happened in the past, such as the Deccan Traps event that occurred in India approximately 65 million years ago and likely covered an area of 1.5 million square kilometers with lava.

"Looking at the geologic record, many scientists agree that the Deccan Traps eruption event caused a large stress on many living creatures," says Jackson. "A future eruption of comparable magnitude would probably cause similar stress levels to life on the planet."

A lot of researchers have speculated that this historical eruption began as a smaller plume, and the only way that a volume of material that large could have built up on its way to the surface is if its roots were near the core-mantle boundary. There are similar plumes in the earth today that seismologists have detected.

"If we can model them more carefully and track them, it lets us place more constraints on the predictions of large-volume eruptions," says Jackson.

In addition to following mantle plumes and, of course, providing answers to important scientific questions, knowing more about what is happening miles underneath our feet helps us comprehend more about the physical world that surrounds us.

For example, another aspect of Gurnis's work is focused on long-term sea-level changes. "Imagine we have the earth today and we have our oceans, which are like water in a bathtub," he explains. "One can imagine that the shape of the bathtub changes with time and your watermark in the tub changes. What we do is create a synthetic planet based upon our geophysical understanding, but one that evolves with known plate motion and is part of a big four-dimensional system."

In the models, low areas are filled with water to see where sea level was high at different points in the earth's history, and where it was low. "The models are then refined using our vast knowledge of the geologic evolution of oceans and continents," Gurnis says.

"Because the earth is a dynamic planet, it turns out that the sea level doesn't just uniformly go up and down everywhere on the planet in a simple way, which is something geologists have been debating for years," he adds. "Rather, what we see is that some continents will move up and others will move down because of the dynamics in the earth's interior. Knowing more about this process will help us predict how that might happen."

For Helmberger, the most practical part of his research is connected with studying earthquakes. "If you model seismograms, you need to know the sources," says Helmberger, who is proud to have 25 past students who are now professors in the field. "Furthermore, if you understand wave propagation, you can just change the frequency and the wavelength and move from studying big structures, like faults, to little bitty ones, like oil traps."

All this knowledge about earthquake *processes* translates to a better understanding and prediction of earthquake hazards—including shaking and flooding, which can have an impact across the globe.

"When you read a lot of modern geology books, they talk about understanding the nonlinear properties of nature," says Helmberger. "Knowing what's going on in the deep interior of the earth not only helps us better understand more surface events, like earthquakes and volcanoes, but also environmental changes and other things that may not seem related at first."

Jackson says the broad nature of studies involving the earth's interior may lead to advances in our knowledge about other planets and help improve our technologies.

"If we can understand the chemistry, dynamics, and structure of our planet's interior, then perhaps we may begin to home in on the nature of other planetary interiors in our solar system," she says.

"In addition, there is significant materials science overlap with mineral physics that can allow researchers to make better, stronger materials by understanding their basic properties under extreme conditions," she notes. (See "Big Small Things Happening Here," page 18.) "It may sound like a far stretch from the interior of the earth, but training the next generation of scientists will help us tackle future problems that need a scientific mind."

At the beginning of Verne's book, the lead character, a professor, must use his scientific mind to crack a code that reveals the exact path into the center of the earth. With the modern methods being pioneered at Caltech, that path is now clear, but the earth is still holding onto some deep secrets. Gazing out his office window, looking toward the San Gabriel Mountains, Gurnis is clearly excited about the journeys ahead.

"Looking at this mountain range, people can't even comprehend the fact that they are moving," he says. "We're on the Pacific Plate, here in Pasadena—part of the same plate that is plunging underneath Japan. It's incredible to imagine ourselves here, in this office, and nearly 10,000 kilometers away from here—we're all moving together! Over hundreds of millions of years, the whole face of the planet changes. All of it rearranges over time—the continents combine into supercontinents and then they break apart. How does the earth do this? How does it work? That's what keeps me going. We're just one planet, but from a human perspective, it's pretty extraordinary that we're part of this incredible bubbling, convecting system that we call home." E&S

Michael Gurnis is the John E. and Hazel S. Smits Professor of Geophysics, and director of Caltech's Seismological Laboratory. *His research is supported by the National Science Foundation, the Gordon and Betty Moore Foundation (through the Caltech Tectonics Laboratory), and Statoil, a Norwegian oil company.*

Donald V. Helmberger is a professor of geophysics and served as director of the Seismo Lab from 1998 to 2003.

Jennifer M. Jackson is an assistant professor of mineral physics. *The National Science Foundation and the Keck Institute for Space Studies at Caltech sponsor her studies.*

ALUMNI IMPACT

Caltech alumni make their mark after leaving the Institute, building upon what they've learned here, building the foundations for new fields of research, even building rockets!

Laurie Leshin

David W. Thompson

Lily Y. Jan and Yuh Nung Jan

Sean Solomon

Richard Scheller

FINDING SPACE

Laurie Leshin
PhD Geochemistry 1995

Laurie Leshin is on a hunt for water. As a cosmochemist, she has spent most of her career searching for wet stuff all over the solar system. She has worked on projects ranging from the recently launched Mars Science Laboratory rover to using meteorites from Mars to assess the potential for life and the history of water on the red planet and elsewhere. The International Astronomical Union recognized her contributions to planetary science with the naming of asteroid 4922 Leshin. Leshin is currently the dean of the School of Science at Rensselaer Polytechnic Institute.

MERCURY RISING

Sean Solomon
BS Geology 1966

Sean Solomon's work has helped shape the understanding of planets far and wide. He is currently the principal investigator on MESSENGER, NASA's mission to Mercury, which has been collecting data since April 2011. The first spacecraft to orbit Mercury, MESSENGER has already survived more than 500 orbits and is sending back tens of thousands of detailed pictures and other information that will help us better understand what the planet is made of, how it evolved, and how its core works. Solomon's research has also explained the resurfacing processes that occur on places like the moon and Mars, which have only one tectonic plate. Solomon is the director of the Department of Terrestrial Magnetism at the Carnegie Institution of Washington, in Washington, DC.

SEEING POSSIBILITIES IN SLUG BRAINS

Richard Scheller
PhD Chemistry 1980

As a newly minted Caltech PhD, Richard Scheller did a postdoc in the Columbia University lab of Nobel Prize–winning neuroscientist Eric Kandel, where they were studying the brains of sea slugs. While looking at slug brains with a microscope, Scheller identified a class of large, white nerve cells whose function was unknown. He proved that these cells supply the chemicals that regulate the slug's egg-laying process—performing one of the earliest experiments to show how a brain can control specific bodily functions. He has since helped decode the genes that control the functioning of vesicles, tiny fluid-filled pockets that release chemicals into the synapses between neurons. In particular, Scheller and a colleague have found that a protein that senses calcium acts as a switch for turning these neurotransmitters on and off. Now executive vice president, Genentech Research and Early Development, Scheller brings his creative perspective to the search for new drugs.

CHANNELING POTASSIUM

Lily Y. Jan
MS Physics 1970
PhD Biophysics 1974
Yuh Nung Jan
MS Physics 1970
PhD Biophysics 1975

Lily Jan spent two years studying physics with George Zweig (PhD '64) before switching to biology, a move that would set her up for the rest of her career. She ended up getting a lot from Caltech: a master's degree, a doctorate, and a husband, Yuh Nung Jan, whom she met as a graduate student. The Jans have shared a laboratory since 1979. In 1987, they were the first to determine the DNA sequence of a potassium channel in fruit flies. This discovery laid the groundwork for studies by the Jans and others showing that potassium-channel mutations in fruit flies cause the same health problems—epilepsy, deafness, hypertension, arrhythmia—as similar mutations in higher organisms, including humans. The Jans work at UC San Francisco, where they continue to study how potassium channels regulate neuron signaling in the brain.

MAKING SPACE

David W. Thompson
MS Aeronautics 1978

David Thompson always had an eye on exploring space. As a graduate student at Caltech, he worked on the first Mars landing missions at the Jet Propulsion Laboratory. In 1982, he cofounded Orbital Sciences Corporation. During his three decades at the company, Orbital has created new classes of rockets and satellites that have helped make space applications more affordable and accessible to people and enterprises around the world. One of the leaders of the American space industry, Orbital makes everything from satellites and launch vehicles to human-rated space systems and missile-defense systems. Thompson continues to serve the company as chairman and chief executive officer, a position he has held since Orbital's inception.

NICHOLAS W. TSCHOEGL
1918–2011

Nicholas W. Tschoegl, professor of chemical engineering, emeritus, passed away on the morning of November 14 at his home in Pasadena. He was 93.

Tschoegl studied how the molecular structures of synthetic rubbers and so-called block copolymers affected how they flow under pressure, a field known as rheology. His book, *The Phenomenological Theory of Linear Viscoelastic Behavior*, remains the authoritative text on the subject.

But "it was Nick's curiosity that set him apart," says Bob Cohen (PhD '72), the St. Laurent Professor of Chemical Engineering at MIT and one of Tschoegl's first graduate students. "I was in his group in the late '60s; young people were looking for gurus, and Nick was ours. The discussions at our weekly group lunches at the Ath were shaped by Nick's passions—the lost city of Atlantis, the structural connections among the dozen languages he spoke fluently, and the demise of central-European nobility in pre–World War II Europe. He treated us like family, opened his home to us, and took us on amazing field trips to see the poppies bloom in the desert or to examine the reflecting pools at Hearst Castle."

Adds John Seinfeld, the Nohl Professor and professor of chemical engineering, "He could discuss virtually any area of history or language with authority. He was a true renaissance scholar."

Tschoegl was born in 1918 in Moravia, which was then a province of the Austro-Hungarian Empire and is now in the Czech Republic. When he was just three months old, his father, a lieutenant in the hussars, was killed in Italy in the waning days of World War I. Raised by his mother, he would spend his formative years in Hungary, Germany, and Czechoslovakia. By age nine, he had become fascinated with electricity, which sparked his interest in science.

At around this time he also developed the passion for languages that would follow him throughout his life. Already proficient in German, Hungarian, and Czech, he went on to study English, French, Italian, and Latin. In high school, he picked up some Turkish and learned the Arabic and Cyrillic scripts. He eventually studied other writing systems, including Egyptian hieroglyphics, Assyrian and Babylonian cuneiform, Chinese, and Japanese.

Upon finishing high school in 1936, Tschoegl was conscripted into the Hungarian Army for a year; when Hungary entered World War II as an Axis power he was recalled to service and eventually sent to the Russian Front as an artillery officer. He survived three major battles, including the siege of Stalingrad, only to be shot in his left shoulder back in Budapest as Soviet forces encircled the city. He was nursed back to health by his friend, Polish medical student Sophia Glazmak.

The two were married in 1946, and had their first son, Adrian, in 1947. The family fled from Communist rule in 1948, with Sophia and Adrian boarding a train to Italy while Tschoegl was smuggled across Lake Fertö, which straddles the Austrian border, in a small boat in the dead of night.

The family eventually settled in Sydney, Australia, where their second son, Christopher, was born. Tschoegl received his PhD in physical chemistry from the University of New South Wales in 1958 and joined the Bread Research Institute of Australia, where he did pioneering work on the rheology of wheat-flour dough. He accepted a position at the University of Wisconsin working on synthetic polymers in 1961, and then spent two years at the Stanford Research Institute before joining Caltech in 1965 as an associate professor of materials science. He became a professor of chemical engineering two years later, and professor emeritus in 1985.

Tschoegl is survived by his son Adrian; a daughter-in-law, Naomi; and two grandchildren, Elizabeth and Matthew. Sophia and Christopher predeceased him.—*MW* E&S

ARON KUPPERMANN
1926–2011

Aron Kuppermann, professor of chemical physics, emeritus, passed away October 15 at his home in Altadena, California. He was 85 years old.

A leader in the field of computational chemistry, Kuppermann was best known for his theoretical studies of the dynamics of chemical reactions. In the early 1970s, he performed the world's first complete three-dimensional quantum-mechanical calculation of a chemical reaction. This feat took more than 1,000 hours of time on an IBM 370 mainframe computer—at the Pasadena campus of the Worldwide Church of God.

As Kuppermann told *E&S* in a 1996 interview, Caltech charged for computer time, and the spanking-new 370—"essentially the world's most powerful" machine—went for $300 an hour. He didn't have that kind of money, but he discovered that the church used an identical machine to process donations, and that their 370 sat idle on weekends. He talked the church leaders into letting him use it, a feat he called a minor miracle, but privacy concerns barred him from physical access to the machine. Instead, he had to drop off his box of punch cards at the cashier's window on Friday afternoon, and on Monday morning the printout—checked to be sure it contained no donor information—was waiting for him. "If they read in my box of cards and one got mangled, that was it—a weekend lost," he recalled, adding however that without that 370 "we couldn't have done the work."

The object of all this labor was the simplest chemical reaction imaginable—an incoming hydrogen atom replacing one of the two atoms in a gaseous H_2 molecule. In later years, Kuppermann pioneered the use of supercomputers to predict the rates and probabilities of reactions involving as many as five atoms. In the process, he developed methods for representing the complex relationships between electrons and atomic nuclei, accounting for all of their possible relative positions and rotations by use of higher-dimensional spaces.

"Aron will be known for the challenging work he did on fundamental quantum-mechanical treatments of the dynamics of chemical reactions," says Nobel Laureate Rudy Marcus, the Noyes Professor of Chemistry and a longtime colleague of Kuppermann. "He always went on, in a pioneering way, to increasingly challenging problems. His use and extensions of hyperspherical coordinates and the equations that resulted from

Opposite: The Kuppermann family. Aron Kuppermann is pictured fourth from the left in the back row.

Below: Aron and Roza Kuppermann were married for 60 years.

them provide a framework that others can follow."

Kuppermann also applied chemical physics to radiation chemistry, and he helped develop electron-impact spectroscopy.

Born May 6, 1926, in São Paulo, Brazil, Kuppermann received his BS in chemical engineering in 1948 and another in civil engineering in 1952 from the University of São Paulo. He earned his PhD in physical chemistry at Notre Dame in 1955. He then worked his way up the academic ranks at the University of Illinois before joining the Caltech faculty as a full professor in 1963. He became emeritus in 2010.

"Aron was an important part of the Caltech family for almost 50 years," says Jackie Barton, chair of the Division of Chemistry and Chemical Engineering, as well as Caltech's Hanisch Memorial Professor and professor of chemistry. "He was concerned about his students and helped always to mentor his young colleagues. He will be missed by all of us." Kuppermann was given the 1999 Excellence in Mentoring Award by the Graduate Student Council (GSC), and a GSC Classroom Teaching Award in 2010. He also worked to improve the state of education and research abroad, especially in his native Brazil. He served on the Joint U.S.–Brazil Science Cooperation Program on Graduate Teaching and Research in Chemistry from 1969 to 1976, with the last three years as chair.

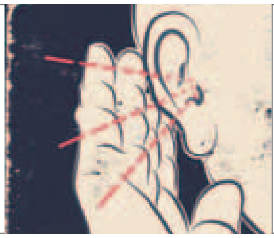
Kuppermann was a fellow of the American Physical Society and the American Institute of Chemists. He was also Councilor for Chemistry to the International Association for Radiation Research and to the Radiation Research Society, as well as a member of the Advisory Panel on Atomic and Molecular Properties for the National Standard Reference Data Program.

Kuppermann is survived by his wife, Roza, and four children—Baruch, Miriam, Nathan, and Sharon. *—KF/DS* E&S

"Aron will be known for the challenging work he did on fundamental quantum-mechanical treatments of the dynamics of chemical reactions..."

WE ASKED CALTECH ALUMS TO SHARE THE ONE LESSON THAT HAS SERVED THEM BEST THROUGHOUT THEIR LIVES. HERE'S WHAT THEY HAD TO SAY:

LISTEN



A back-of-the-envelope calculation works 99 times out of 100.

How much work I could get done at the last minute.

A Caltech alum can learn to do anything.

The honor system! It has ruled my life . . . and my golf game.

Bohnenblust's admonition that no partial credit would be given: *"When the bridge falls down, no one cares that you used the right formula."*

Surrounding yourself with smart people really *does* make you smarter.

Don't wait until you get your PhD to get married if the right person comes along.

There are "rules," and then there are the real rules. You solve problems by not following the "rules."

Hardy Martel [BS '49, PhD '56] taught me how to model a system: "Assume the hell out of it until you can solve it. Then add the bells and whistles."

Work hard, but take interesting vacations.

Never say, "I'll never use this stuff. Why do I have to take this course?"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