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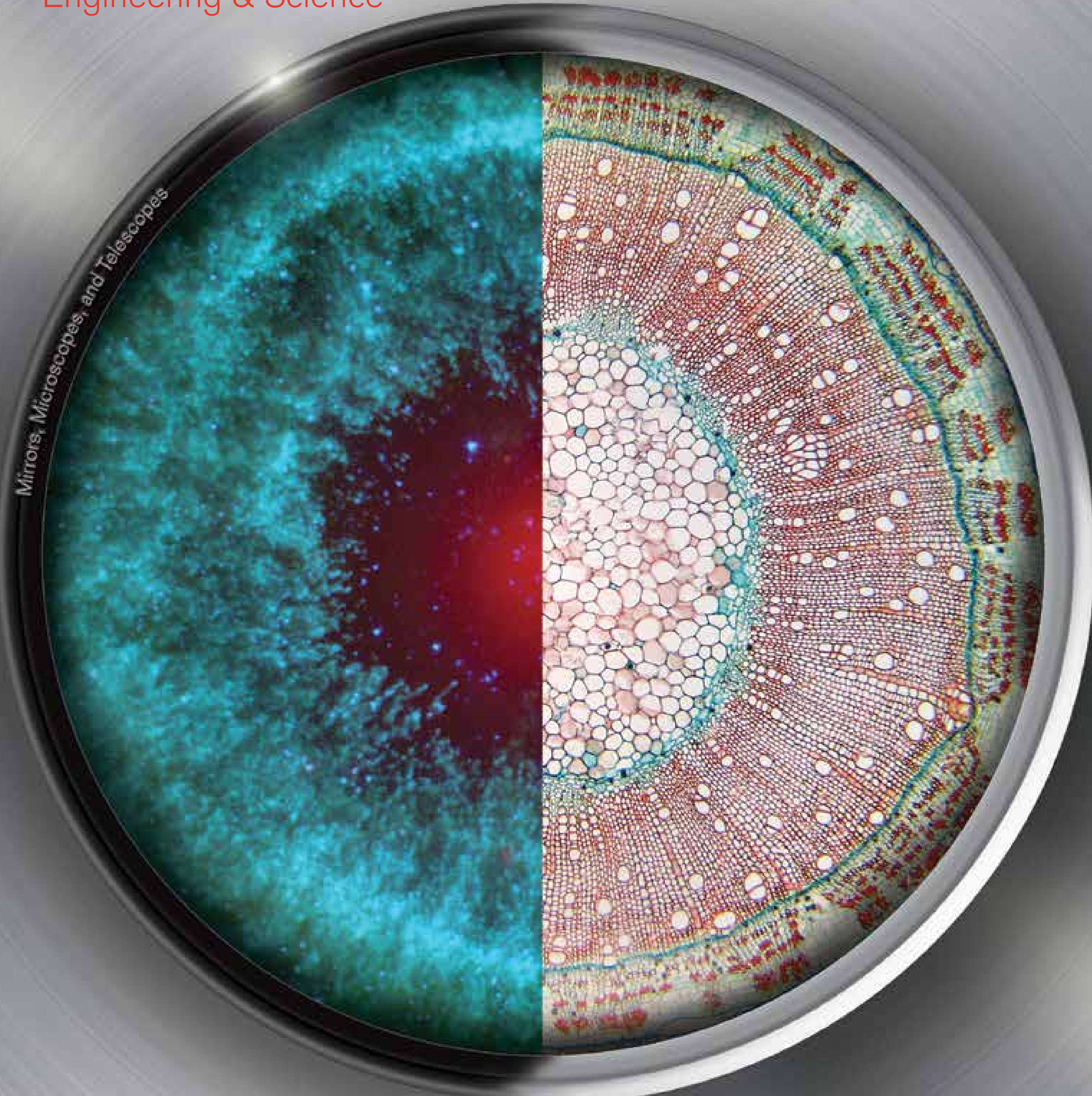

Caltech

VOLUME LXXVII, NUMBER 2, SUMMER 2014

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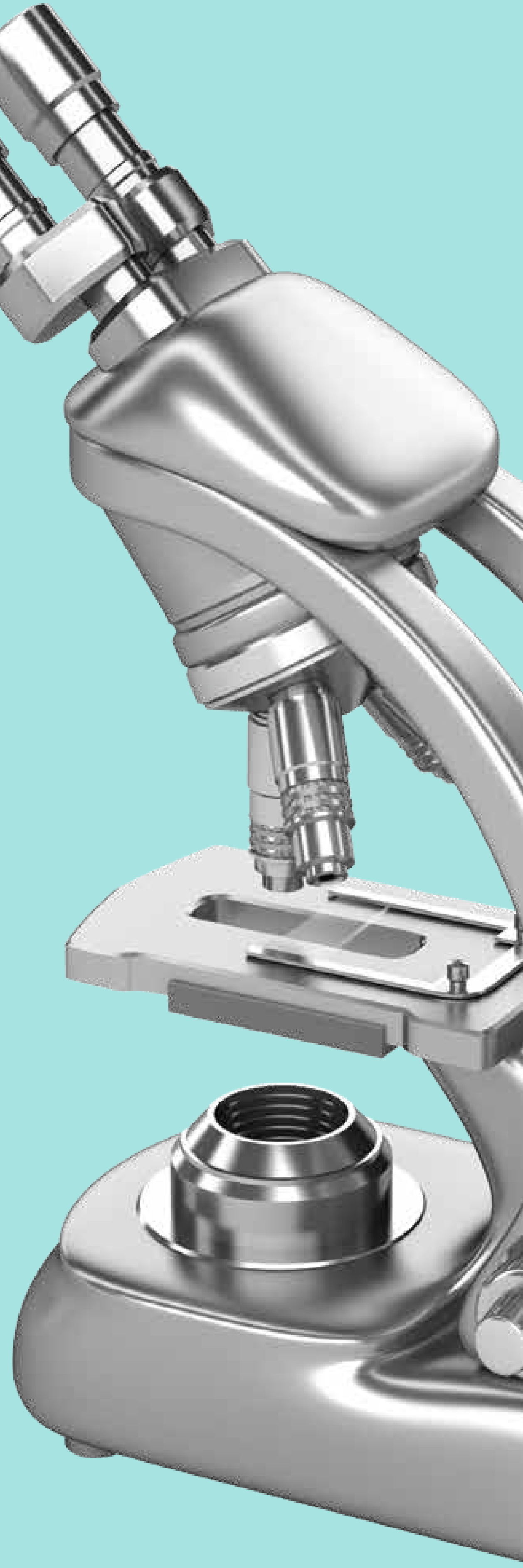
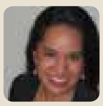


Caltech on Twitter

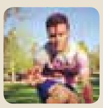
Follow us, retweet us, and let us know you're talking about us by including @Caltech in your tweets.

@aumphy: Sitting in on @Caltech lecture on the origins of metabolic engineering. We're 30 minutes in and I just now heard a word I understood: yeast.

@trueanomalies: Gotta say, I really enjoyed seeing both @Caltech and Meteor Crater featured in @COSMOSonTV in "The Clean Room"! #cosmoschat

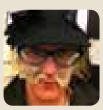


@cacanaria: @Caltech, you are #audacious without a doubt. Showing @mit some #prankster love. #caltechalumni proud. #iwantone http://t.co/dFzHjIqJXx



@JadenGeller: Looks like @Caltech is rebranding themselves with a new logo—even released a style guide! So much more elegant. I'm pleasantly surprised!

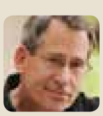
@lolitanbcla: @Caltech @USGS thank you for keeping us informed and speaking to us reporters! Your knowledge helps inform and educate immensely! #Chile



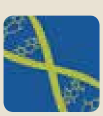
@wraavr: Drs. Lucy Jones, Egil Hauksson, and Kate Hutton do a tremendous job of bringing earthquake science to Californians! #caltech #usgs

@VitaminWomen: Of the 80 highest ranked schools in the country, our top 10 best colleges for women http://t.co/47T1TF9xxt @BU_Tweets @caltech @CC_Columbia

@NSF: Why STEM? 'There is nothing better than learning about how the world works' @Caltech chemist JK Barton #WomenNSF http://t.co/5gvoGCiyvg



@preskill: Student @Caltech on 2014 Feynman Teaching Prize winner: "I want to be like Professor Frautschi when I grow up." http://t.co/KAIGMcdonJ



@genentech: gRED EVP Richard Scheller named @Caltech Distinguished Alum! Read abt his early days in the lab: http://t.co/YIt0V1bJm5 #TBT

Caltech Engineering & Science

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Reflecting on Caltech

Around our office, we often talk about how some of the key technologies used at Caltech—mirrors, microscopes, and telescopes—are also symbols of the Institute's relationship to the world at large. The work being done at Caltech reflects questions and issues vital to society, and our researchers are committed to taking a close-up look at the best solutions while simultaneously considering their far-reaching impact.

And so we decided to dedicate this issue of *E&S* to exploring those symbols—those mirrors, microscopes, and telescopes—in all their literal and figurative glory.

To begin with, we take eight pages to consider the findings of the BICEP2 telescope (see page 10), which was born and bred right here at Caltech, and whose team has made remarkable findings about what happened to the universe at the time of the Big Bang, sharing them to great acclaim and—as I like to point out to my colleagues—at a perfect time in our editorial cycle. (I'm sure that was top-of-mind for the team as they assessed their data, and I won't be told otherwise.) In addition to our story about how the telescope came to be is a short essay from Caltech's own physicist-about-town, Sean Carroll, who reflects on what the findings mean and why they are indeed a "scientific and technological tour de force."

We decided to dedicate this issue of *E&S* to exploring those symbols in all their literal and figurative glory.

Also in this issue is a look at the myriad ways in which Caltech's scientists use mirrors (see page 20) as an integral part of research that ranges from looking at the ways in which cells interact with objects in their environment to the search for gravitational waves. You'll also want to check out our take on a 15th-century globe (see page 18) that shows how artifacts can capture and reflect past worldviews.

Finally, because—depending on when you read this—we either will be welcoming or will just have welcomed Caltech's ninth president in the Institute's history, we've included a short Q&A with Thomas F. Rosenbaum (see page 26), who shared with me his thoughts on Caltech's uniqueness, the challenges facing higher education, and what sealed his decision to come to Pasadena.

I hope you'll find that this issue reflects not only where Caltech is today, but your own experience of the Institute as well.

—Lori Oliwenstein, Editor

Random Walk

HOLLOW PILLARS TO HOLD TINY NEEDLES

Although these pink and green structures look like exotic blooms, they're actually made of carbon nanotubes—and they might one day make shots less painful. Made at Caltech by Adrianus Indrat Aria (MS '08, PhD '13), a former graduate student in the laboratory of Morteza Gharib, Hans W. Liepmann Professor of Aeronautics and Bioinspired Engineering, these flowerlike projections are made by "growing" densely packed nanotubes—long, cylindrical, crystalline carbon nanostructures—into a vertical stem on a silicon wafer. The researchers then rearrange the nanotubes into the hollow-pillar configuration. Only a few tens of micrometers wide and a millimeter tall, the tiny pillars hold equally tiny composite microneedles, which are envisioned for future use in medicine as a replacement for the commonly used hypodermic ones. The researchers hope that these hollow pillars and microneedles could pave the way for self-administered and pain-free therapeutic and diagnostic systems in the future.

BY THE NUMBERS

Basketball en España

The Caltech men's basketball team became an international sensation this spring, traveling to Spain and dominating games against local teams in the Catalonia region. The trip across the Atlantic, the first for a Caltech athletics program, spanned the Institute's spring break from March 20 to March 29. Led by head coach Oliver Eslinger, the team played four exciting games against experienced club teams and was overwhelmed by the warm welcome received from fans. Hugs and handshakes, photographs and autographs were all part of the postgame festivities. "I've never experienced anything like it; I really felt like we won a national title or something," says then freshman Nasser Al-Rayes. In addition to shooting hoops, the team took in the sights in Barcelona, Montserrat, Girona, and other locations along the Catalan coast. "The best thing about the trip was being able to vacation and play competitive basketball at the same time," says Ricky Galliani, also a freshman at the time. "It was a rare, special opportunity."

15
Number of Caltech men's basketball players who traveled to Spain.

3
Number of consecutive wins by Caltech over Spanish teams.

65
Average number of points scored by Caltech per game.

174
Total number of rebounds by Caltech players in their four games.

1,535
Kilometers traveled in Spain by the team for games and sightseeing.

Icy in the Sky with Ovals

Fifty miles above the earth's polar regions—where the pressure is 100,000 times lower than at sea level, and the temperature is a frigid –1,900° F—tiny grains of ice can form phenomena known as noctilucent clouds. Visible just after dusk in northern cities like Stockholm, these wispy formations are much higher than—and quite unrelated to—the other clouds we're used to here on Earth. In the past, researchers thought that the ice grains in these clouds would be tiny spheres, but a recent study in the laboratory of applied physicist Paul Bellan suggests that the grains might actually be much more elongated—a property that may help scientists better understand these curious clouds.

Noctilucent clouds—as well as the tails of comets and a few of Saturn's more diffuse rings—are examples of "dusty plasmas." Plasma, a gas of freely moving electrons and ions, is one of the four states of matter. When dust particles (such as tiny ice grains) enter the equation, they capture electrons from the plasma and become electrically charged, forming a dusty plasma.

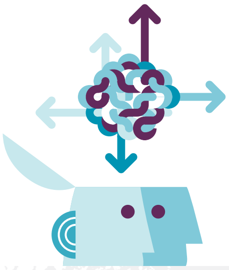
Rather than studying the actual formation of ice grains high above the earth, Bellan and postdoctoral scholar Kil-Byoung Chai decided to make a water-ice dusty plasma in the laboratory. They did this by injecting water vapor into an electron-ion plasma in a vaccum chamber at low temperature and low pressure—conditions similar to those needed for the formation of noctilucent clouds.

The result? Oval-shaped ice particles that are four times longer than they are wide. Spherical shapes can easily be used in calculations and models, so many physicists assumed nature would also reflect this simplicity. Bellan and Chai were the first to show experimental evidence contradicting this assumption.

Because ellipsoidal shapes react with light and radio waves much differently than their spherical counterpart, those elongated ice grains could also explain another curious property of noctilucent clouds: their interaction with electromagnetic radiation.

Although Bellan's experiment in the laboratory can't confirm that these tiny ovals are responsible for the behaviors of high-up noctilucent clouds, the results will give scientists a new possibility to ponder. —*JSC*

> "While diminutive scale may be a disadvantage for some institutions, for Caltech, it is at the heart of its being, and perhaps the single most important aspect of its extraordinary global success."
>
> —*Phil Baty, in "Caltech: secrets of the world's number one university,"* Times Higher Education, *February 6, 2014*



Neural Tiebreakers

That tough choice you're mulling over? Don't give it another thought. Your decision might hinge on unconscious brain processes that took place before you even began deliberating, according to a new study led by Uri Maoz, a postdoctoral scholar in biology and biological engineering.

The researchers first trained monkeys to associate particular on-screen cues with being given either a smaller amount of fruit juice right away or more juice a little later. The researchers then repeatedly offered the monkeys a choice between the two, randomizing the cue locations and delay durations to make sure the monkeys didn't know which cues to expect. The scientists then tried to predict, based solely on brain activity that took place before cue onset, which target the monkeys would choose.

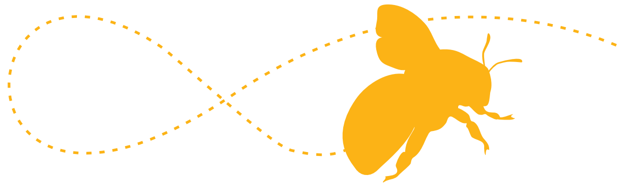
"It turns out that if a monkey had a harder time choosing between the options—when the two choices were of similar value—we were able to predict which option it would choose before rational deliberation could begin," Maoz says.

Looking at two areas of the brain—the dorsolateral prefrontal cortex and the striatum—the researchers identified populations of neurons that were predictive of behavior even before the monkeys were shown their choices. Activity in one class of these so-called bias neurons predicted whether a monkey would choose the cue on the right side of the screen or the left, while a separate class predicted whether a monkey would select the larger or smaller reward.

Maoz says when the decision is easier—for example, when the monkey is given a choice to receive a large amount of juice right away—the bias activity gets overridden. The researchers, who published their findings in the journal *Frontiers in Neuroscience*, hypothesize that these bias neurons may exist essentially to help break ties. Imagine being faced with an obstacle in the middle of the road. A decision to swerve to the left or to the right to avoid it might be similarly good, Maoz says. "It may be better to make a choice quickly—even a slightly worse one—than to make no choice at all. That is where neural tiebreaking comes in handy." —*KF*

Insider Info

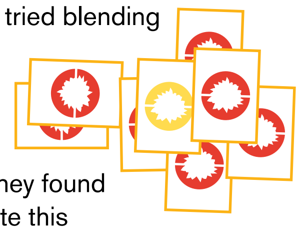
Detectors at LIGO (see page 23) are so sensitive that the gravitational pull of a **bumblebee** flying outside the building could set them off.



The *E&S* art department tried blending

75

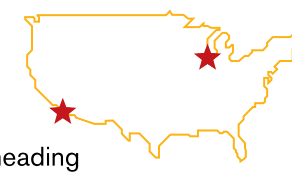
different photos before they found the right match to illustrate this issue's theme, "Mirrors, Microscopes, and Telescopes," on the cover.



Caltech's new president, Thomas Rosenbaum, spent

31.25

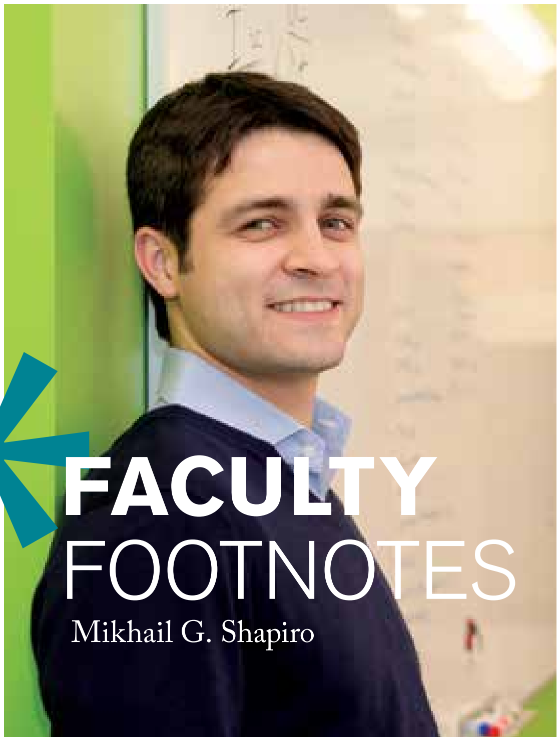
years in Chicago before heading for the sunnier skies of Pasadena. Find out what brought him to Caltech and more on page 26.



On the Grounds

The variegated tiles on this staircase, located in one of the two structures with LEED Platinum certification on campus, are not simply a happy flourish intended to brighten your day. They were designed as an homage to the colors of the visible spectrum of light, which is an essential component of the work performed inside the building. The researchers here are working to harness the powers of the sun to produce chemical fuels and provide a more sustainable future. So where at Caltech can you get a glimpse of these prismatic steps? See below for the answer.

Answer: These colorful steps are part of the central staircase in the Earle M. Jorgensen Laboratory.



FACULTY FOOTNOTES

Mikhail G. Shapiro

This January, Assistant Professor of Chemical Engineering Mikhail G. Shapiro joined the Caltech faculty. His laboratory is working to create "molecular reporters," or molecules that can be introduced into the brain to enable more precise observation of the brain's function. Shapiro engineers these reporters based on proteins and other molecules that can interact with sound waves or magnetic fields so they can be imaged noninvasively using technologies such as MRI and ultrasound. He hopes to collaborate with other engineers and neuroscientists to use these technologies to study how neural circuits function and what happens to them when neurological and psychiatric diseases strike.

Here are a few more things you might find interesting about Shapiro:

- He didn't set out to be a chemical engineer: *"I started out as a political science major, but then I got drawn to science in college. The mysteries of the brain are very seductive."*
- Before he wandered the halls of academe, he wandered the halls of Congress. *"I served as a page in the House of Representatives."*
- As he has pursued his education, he has moved steadily westward, apart from a small dodge eastward to attend Brown University as an undergraduate. *"I grew up in Soviet Russia until age 11, and then we moved to Washington, D.C., where I went to high school. I did a PhD at MIT, a brief postdoc at the University of Chicago, and then I was a Miller Fellow at Berkeley before coming to Caltech."*

A Class Act

In the hunt for renewable energy resources, researchers around the world are racing to discover photocatalysts—materials that provide efficient methods for making solar fuels from water using energy from the sun. And now, thanks to outreach efforts at the National Science Foundation's Center for Chemical Innovation: Solar Fuels (CCI-Solar)—in which Caltech is a partner—kids across the globe can join the race as well.

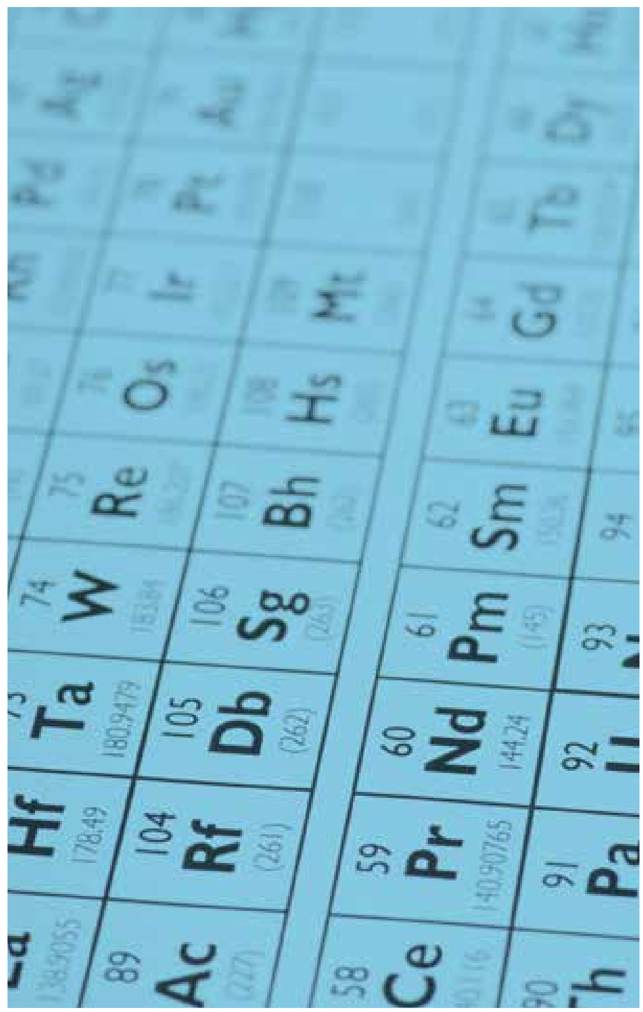
The Solar Energy Activity Lab (SEAL) project distributes research kits that allow students in more than 90 middle and high schools around the world to discover inexpensive metal oxide semiconductors that could efficiently split water into hydrogen (to be used for fuel) and oxygen using sunlight.

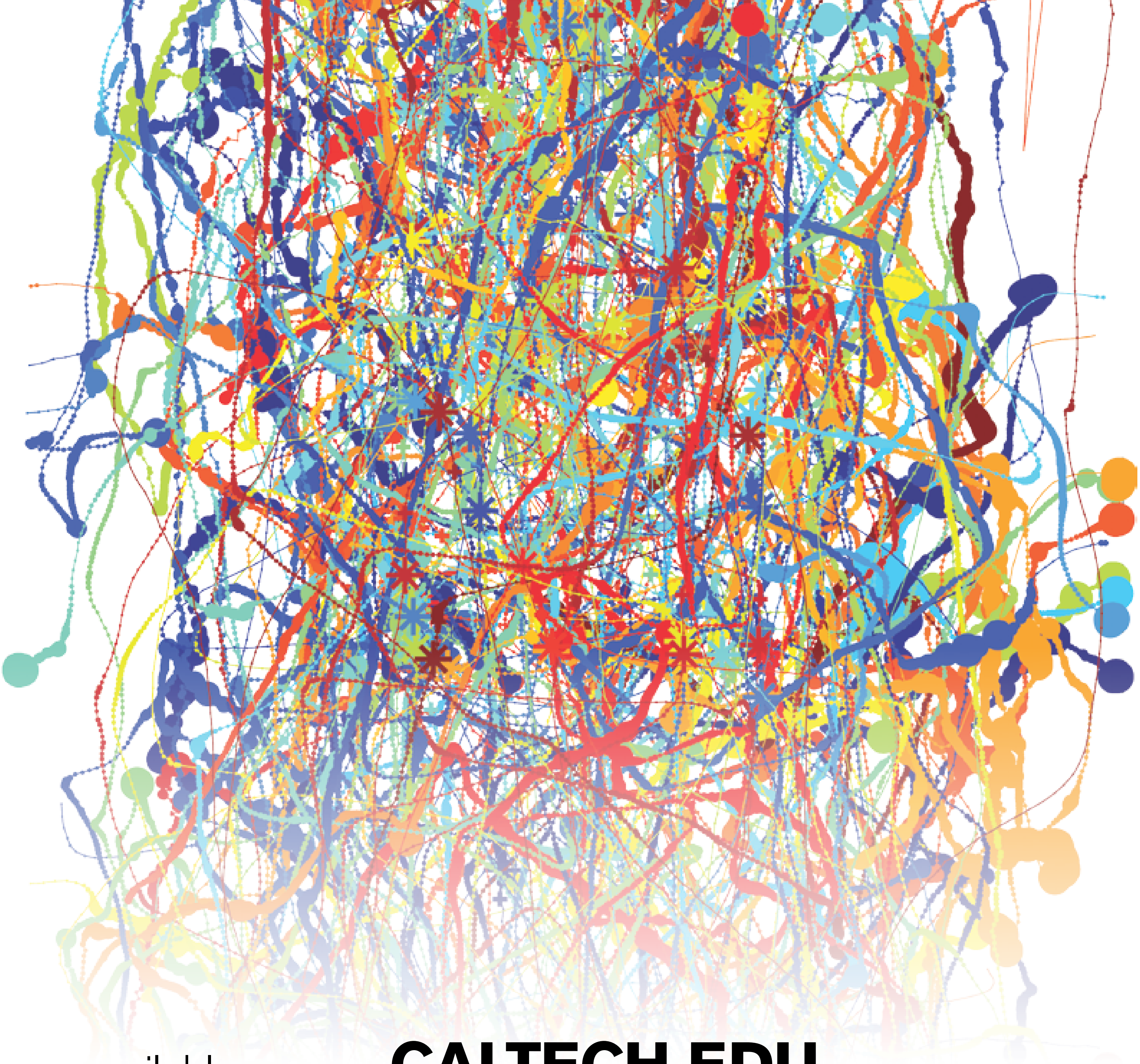
With the kit, the students make different combinations of the metals listed on the periodic table, placing tiny spots of the mixtures on a glass plate that can act as a conductor of electricity. To test a combination's efficiency as a photocatalyst, the students pulse an LED light at each spot while a detector measures the electrical current in the system.

If a large increase in current is detected, it means that the metal mixture could be a good photocatalyst candidate, and researchers at CCI-Solar can follow up with additional analyses. After performing their experiments, many of the students are invited to present their research at the Southern California Solar Army/SEAL Convention, held each May at Caltech.

SEAL and CCI-Solar's other outreach projects provide a way for young people to learn about chemistry while also contributing to actual research that will change the way we power the world. —*JSC*

To see Caltech's CCI-Solar team in action, check out the video at http://www.nsf.gov/news/special_reports/science_nation/solarfuels.jsp.





available now on **CALTECH.EDU**

IN-FLIGHT TURBULENCE

A Caltech bioengineering team has uncovered a mechanism for how fruit flies regulate their flight speed, revealing an important relationship between the insect's vision and its wind-sensing antennae. The image above is a tracing of the flies' flight trajectories, scaled according to speed. Learn more at **caltech.edu/news**.

Watch

Caltech geochemist and paleoclimatologist Jess Adkins talks about the history of climate change, where we are today, and what we can do to mitigate its impact in the future. Check out the video at **youtube.com/caltech**.

Read

Find out how Caltech's scientific, engineering, and technological achievements advance understanding, improve our quality of life, and transform the future. Dive in at **caltech.edu/content/our-impact.**

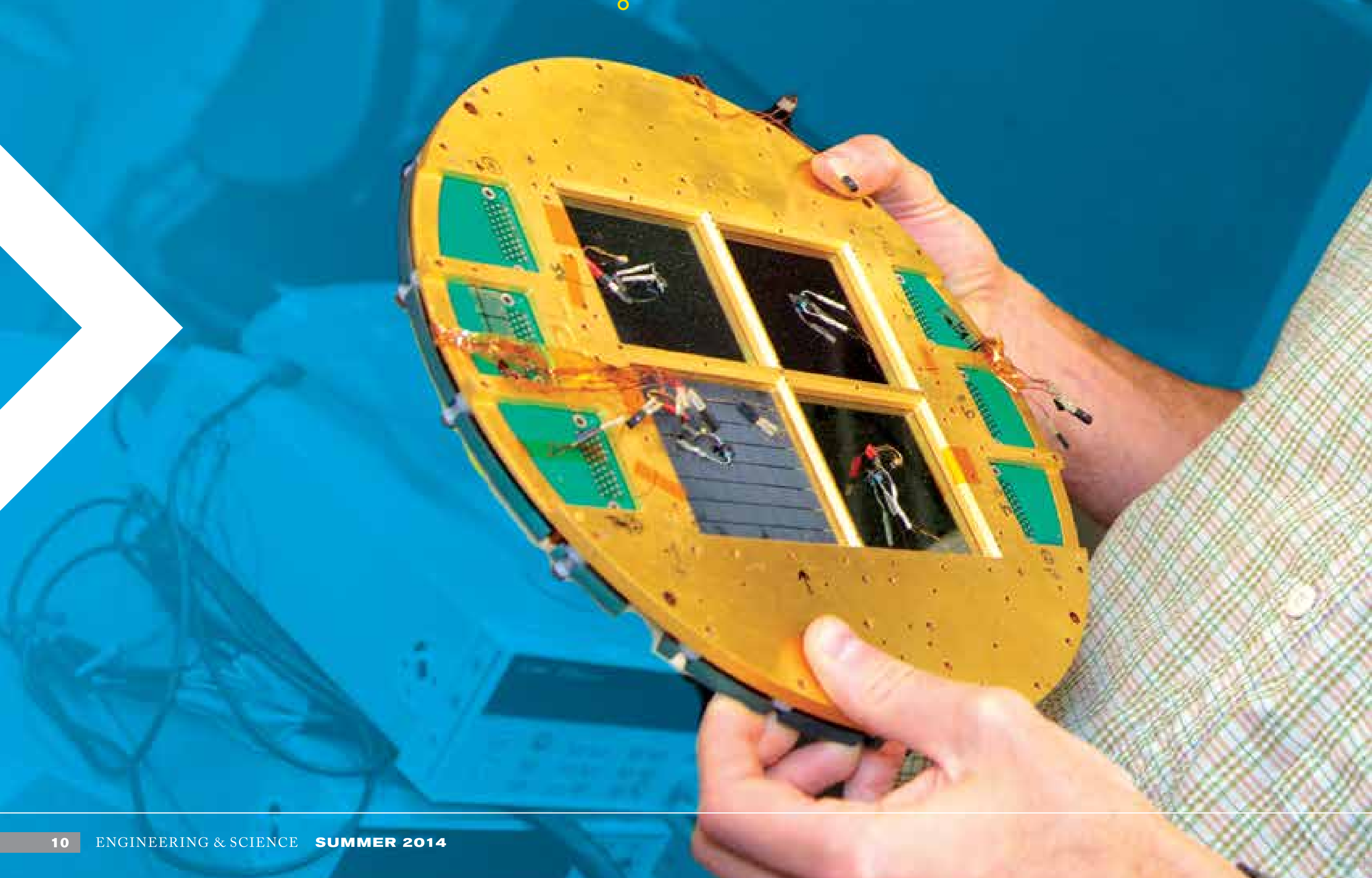
Engage

Enjoy music under the stars when MUSE/IQUE returns to the Caltech campus on Saturday, July 5 at 7:30 p.m. Find out more at **caltech.edu/calendar/public-events**.

Small and Mighty

How cosmology has been dramatically changed by a telescope born and bred at Caltech and stationed at the literal end of the earth.

by Cynthia Eller



Caltech professor of physics Jamie Bock holds a dummy version of the focal plane for BICEP2, for use in thermal tests.

Even the most dedicated explorer of the cosmos needs the occasional diversion. When physicist Jamie Bock was a research scientist at JPL back in 2001, that diversion was tennis. Of course, if Bock had wanted a real diversion, he shouldn't have been playing tennis with Brian Keating, then a postdoc at Caltech. The two inevitably ended up talking about their work—measuring the early universe.

As Bock recalls, "Brian kept insisting we should build an experiment to search for direct evidence of the inflationary epoch at the beginning of the universe—a single brief, intense event that blew our observable universe up from a volume smaller than an atom, with space itself expanding faster than the speed of light. For a while I just listened to Brian. Of course this would be something worth finding, but technically it was an enormous challenge. But then I began to think, 'Maybe we really could do this.' Brian was pretty engaged with theoretical astrophysicists, and I liked to design new experiments, so it was a nice combination. I also like small telescopes, from my days flying compact instruments on sounding rockets and satellites. So we came up with the idea of building a simple refracting telescope with a wide field of view that gathers a lot of light."

By 2006, Bock and his colleagues at Caltech and JPL had built the experiment that Keating was pushing for. They called the project BICEP—and in March 2014, data from its second-generation telescope, BICEP2, was presented to the world. The findings were immediately hailed as the greatest cosmological discovery of the 21st century, or perhaps even since the 1920s, when Edwin Hubble realized that the universe is expanding.

Perhaps most impressive is the fact that this detection was achieved by a modest telescope—imagined, designed, and built at Caltech—whose eye on the sky was only 26 centimeters in diameter.

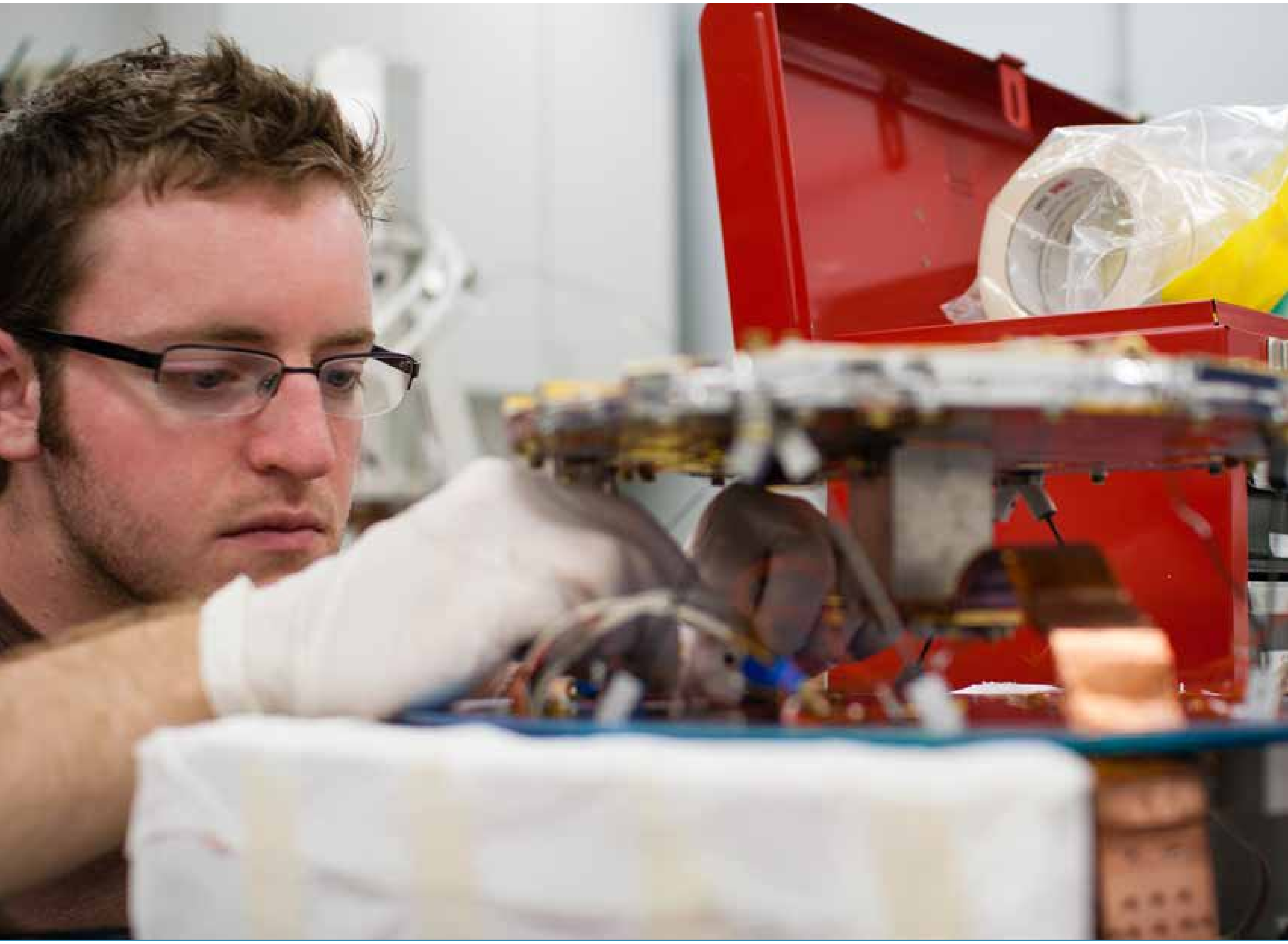
What BICEP Found

From less than a millisecond after the Big Bang until 380,000 years later, the universe was a soup of free electrons and ions. Light particles (photons) could not travel very far during this time before running into a free electron and being scattered. But at 380,000 years, the universe cooled enough so that free electrons combined with free protons to make neutral hydrogen, and the universe became transparent to light.

The earliest electromagnetic radiation we can observe from Earth is the cosmic microwave background (CMB). This light is not visible to the eye, but is observable in all directions from Earth by telescopes using specialized detectors tuned to microwave frequencies. When we make maps of the CMB, we are basically getting a view of the universe at an age of 380,000 years, when the primordial photons from the Big Bang last scattered.

While the CMB is one of the best ways to study the early universe, it also acts as a wall preventing a view of earlier times. It is a bit like looking at the sky on a cloudy day. You can see the surface of the cloud, which is lit up by the sun behind it, but you can't see into the cloud or see the sun itself. To gather evidence for inflation, which occurred behind the wall of the CMB, well before the universe was transparent to light, cosmologists must look for some type of signature that inflation left behind on a later era of the universe that is visible to us: namely, the CMB.

The theory of inflation was first proposed by Erast Gliner in the Soviet Union in 1965, and in 1975 Leonid Grishchuk predicted that massive gravitational waves would have been released in an inflationary scenario. The term itself, "inflation," was coined by MIT's Alan Guth in 1980, and theoreticians from that time forward—including Stanford's Andrei



Linde—assumed that one consequence of their proposed inflationary period would be the highly energetic creation of gravitational waves, which squeeze and stretch space as they travel at the speed of light.

Gravitational waves are notoriously difficult to detect, so it did not occur to cosmologists to try to confirm inflationary theory through the direct detection of gravitational waves. But then, in the late 1990s, theoreticians such as Marc Kamionkowski, on the Caltech faculty from 1999 to 2011, began to suggest that even if gravitational waves themselves could not be detected, perhaps their impact on the CMB, in the form of polarization patterns, could.

Polarization patterns in the CMB can be produced both by density variations, which are largely responsible for the temperature variations in the CMB, and by gravitational waves. But gravitational waves, because they squeeze and stretch space in a unique way, would create a special kind of polarization known as B-mode polarization: a swirly pinwheel pattern that can turn either clockwise or counterclockwise. The conclusion? Find this polarization pattern, and you have found primordial gravitational waves from inflation.

Sound simple? Maybe in concept, but not in execution. The predicted B-modes are such tiny fluctuations in the CMB that most scientists thought it would be impossible to ever detect them. "BICEP was the first experiment of its kind to go after just the B-mode polarization in the CMB," says Bock. "This was scientifically risky, because there was no guaranteed signal. But this was an appealing challenge for us. It was 'B-modes or bust.'"

Left: Former Caltech graduate student Randol Aiken adjusts the BICEP2 telescope in the Caltech highbay laboratory.

Building BICEP

Using Kamionkowski's rationale, Bock and Keating took a proposal to the late Andrew Lange, the Marvin L. Goldberger Professor of Physics at Caltech, for the construction of a small refracting telescope, not unlike the one Galileo used over 400 years ago. The telescope would measure the CMB over a comparatively large portion of the sky—about 5,000 times larger than the face of the full moon—which is enormous compared to the usual targets of astronomical observation.

Lange was on board from the start. Although he knew B-mode detection was a long shot, he deemed the potentially revolutionary result worth the risk. In 2002, the Caltech-JPL team was granted seed money from the Caltech President's Fund, and they were on their way.

Since Kamionkowski had talked about the B-modes as "curls," Keating decided the telescope that searched for the curls should be named "BICEP." From there, he came up with the name to back up that acronym: Background Imaging of Cosmic Extragalactic Polarization.

BICEP involved a dual challenge: creating a new telescope and inventing a revolutionary detector technology to put inside it. Taking on both challenges at the same time was untenable, so Bock decided to use detectors they had successfully designed and deployed on an earlier instrument, BOOMERanG (Balloon Observations of Millimetric Extragalactic Radiation and Geophysics). These detectors were "spiderweb" bolometers, first developed in 1993, that used a fine mesh to absorb millimeter-wave light and convert it into heat sensed by a tiny thermometer.

BICEP2 Buzzwords

Inflation The expansion of space at the time of the Big Bang, when the early universe grew exponentially at a rate that was much faster than the speed of light. Inflation is believed to have happened over an extremely short period of time—mere fractions of a second—after which the universe settled into a much slower rate of expansion that continues today.

Cosmic microwave background (CMB) A relic glow from the early universe. The CMB emits energy at a microwave frequency and is not visible to the naked eye but is observable across the entire sky with the use of specialized telescopes.

Polarization The orientation of the electric field in a light wave. Polarization can be produced by scattering, such as when light glances off the hood of a car.

Gravitational waves Ripples in the fabric of space-time that stretch and squeeze space as they travel. Gravitational waves are created by explosive astronomical phenomena. Gravitational waves from the Big Bang are sometimes called primordial to differentiate them from gravitational waves produced by events like supernovae.

B-mode A pattern of **polarization** that has a characteristic pinwheel shape. BICEP2 detected a B-mode pattern imprinted on the **CMB** by **gravitational waves** produced during the epoch of **inflation**.

Bolometer A detector that absorbs electromagnetic radiation, converting it into heat, and then measures the temperature of the absorber with a sensitive thermometer. The bolometers in BICEP2 measure power at microwave frequencies to detect the **CMB**.

"Back in 2001 when the BICEP project began," says Bock, "we had revolutionary new detectors in mind. These detectors were the successor to the spiderweb bolometers, but they were just emerging, and we needed time to develop and test them. So the first stage was to build and field a practical instrument, BICEP1, with spiderweb bolometers onboard, but the telescope was designed to accommodate the new detectors when they were ready."

One Cool Telescope

BICEP was designed from the beginning to run in a cold environment, colder even than its planned location at the South Pole. Encased in a cryostat—a glorified thermos—the inner workings of BICEP are chilled to .27 kelvins (around –272 Celsius), close to absolute zero and even colder than the CMB itself, the average temperature of which is 2.7 kelvins.

But why so cold? "By cooling the telescope," Bock explains, "we reduce emission from the instrument that the detectors will sense along with the incoming CMB radiation that we want to measure."

The team installed its first telescope—BICEP1—at the South Pole in November 2005. Because the telescope was so small, all that was needed to install it was to cut a hole in the ceiling of the Dark Sector Laboratory, place the BICEP telescope on its mount, and point it at the CMB in a patch of the sky the team calls the "southern hole"—a region without much gas and dust from the Milky Way in the foreground.

By this time, the BICEP project was on a firmer financial footing, thanks to continued support from Caltech, which funded key postdoctoral fellows; the National Science Foundation, which gave major grants to BICEP1 in 2003 and BICEP2 in 2008; and generous gifts from the estate of John M. Robinson, the Gordon and Betty Moore Foundation, and the John B. and Nelly Llanos Kilroy Foundation. JPL supported instrument and technology development through its Research and Technology Development program.

With BICEP1 successfully deployed at the South Pole, Bock and his team, including Chao-Lin Kuo, then a postdoc at JPL and now a professor at Stanford, were back in Pasadena crafting the next-generation detector technology for BICEP2: a radically different, all-in-one detector made from an integrated circuit, a concept pioneered by Jonas Zmuidzinas, the Merle Kingsley Professor of Physics at Caltech and chief technologist at JPL. BICEP2's detector combined bolometers—which detect light—with imaging polarimeters that collect and filter light and analyze the polarization. "Our approach was basically to make a polarization-sensitive camera via a printed micro circuit board," says Bock.

Calibrating and testing BICEP2's flat detectors was a frenzied process in the run up to their deployment at the South Pole in 2009. Jeff Filippini, the Robinson Postdoctoral Fellow in Experimental Astrophysics, remembers that the entire team had doubts about whether or not they would be ready in time: "Even a month before deployment, we were afraid it was never going to work. It's a bit like theater: in the last days of rehearsal, you're sure it will never come together, but somehow it works on opening night."

Indeed, even when the construction of BICEP2 was under way, it seemed that everyone on the project believed that it would turn out to be simply a test run, a learning experience in how to use the detectors. According to Zak Staniszewski, a Caltech postdoc who joined the BICEP2 team shortly before deployment, John Kovac—a Caltech postdoc, now a professor at Harvard, whom Lange had named as the leader of the BICEP2 NSF proposal—urged on the new recruits, saying, "You guys need to learn how to make BICEP2 work so you can make the next telescope work."

But once deployed, the new detectors did their job brilliantly: "BICEP2 was able to get to the same sensitivity as BICEP1 in a tenth of the time," says Bock. "It would have taken BICEP1 30 years to get the results that BICEP2 gathered in just three."

A great advantage to the BICEP2 detectors-on-a-chip is that they can be fairly easily replicated—you print another circuit board—unlike the spiderweb bolometers with their individualized optics that were installed in BICEP1. So with BICEP2 in the field, a follow-on experiment was funded by the W. M. Keck Foundation in 2007 that would gather five BICEP2 telescopes in a cluster to take the most sensitive measurements of the CMB to date. The Keck Array began making observations at the South Pole in 2010.

Surprising Data

And so it was with more than a little surprise that the analysis team, led by Clem Pryke of the University of Minnesota, noticed something curious about the data BICEP2 had gathered in its three observing seasons at the South Pole from 2009 to 2012: it showed a pinwheel polarization pattern in the CMB.

At first, no one on the BICEP2 team believed this pinwheel polarization signal was anything other than a measurement artifact. "At the time, we were trying to get out a paper setting a maximum amplitude on the gravitational wave B-mode signal," recalls Bock. "So this extra signal was a source of some frustration." The situation came to a head at a project collaboration meeting when one of the postdocs compared the BICEP2 data with new data coming in from the Keck Array. The data matched. "That was a pivotal moment," says Bock. "We stopped trying to explain the excess away and started asking ourselves, 'How can we test if this signal is real?'"

The four senior members—Kovac, Pryke, Bock, and Kuo—

BICEP2 team members deliver liquid helium to cool the telescope at the South Pole.

held long phone calls to decide if there were other sources of error and how to tackle each potential source of error in sequence. "Ultimately the most convincing evidence," says Bock, "was seeing the B-mode polarization signal not only in BICEP2 but in the new Keck Array data. Also, given the BICEP2 map, we could find the B-mode polarization in the noisier BICEP1 data. Our result is really a testament to the full program of experiments, and if any of the stages were missing, we would not have been so confident."

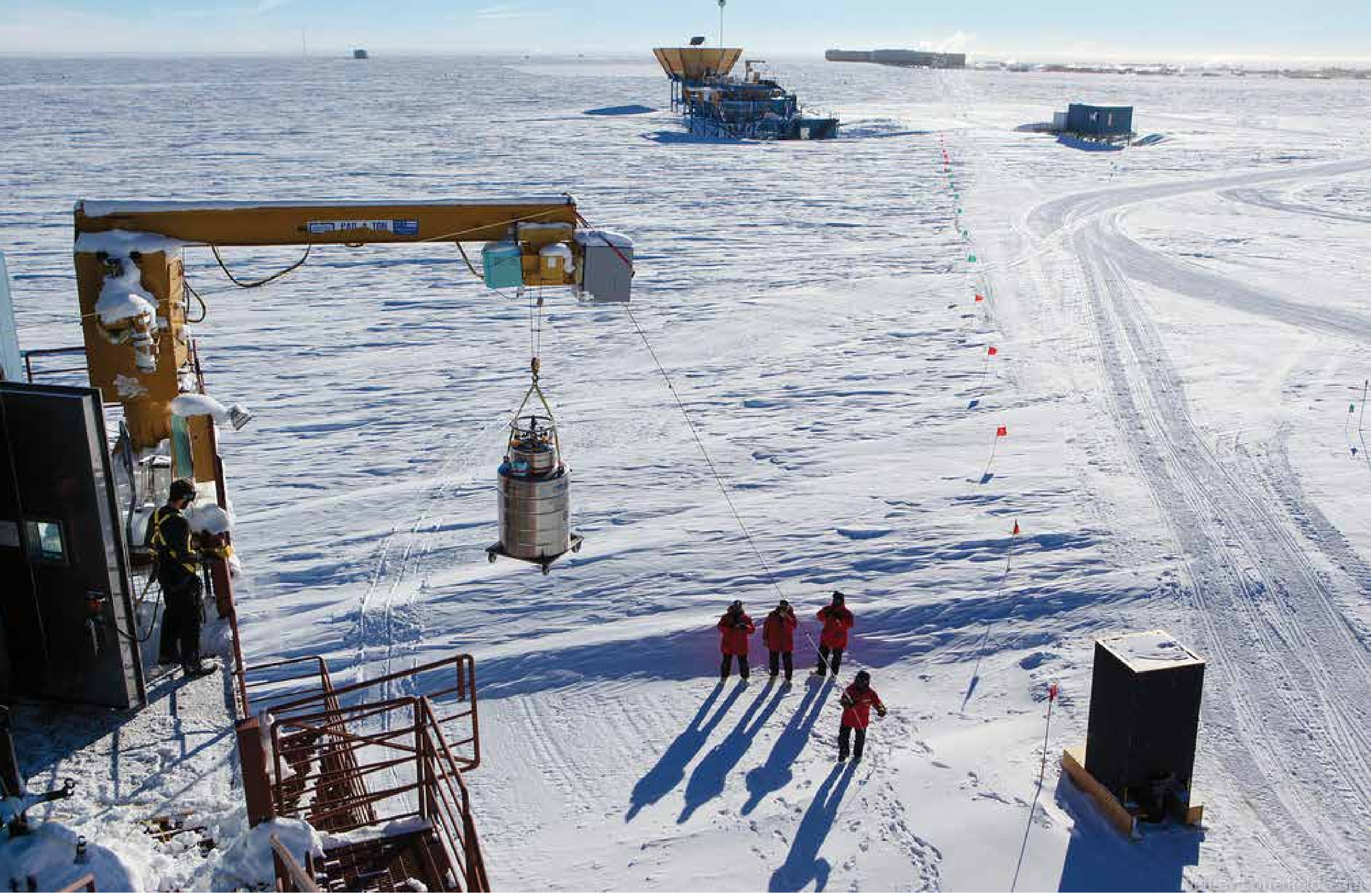
By late 2013, the BICEP2 team was finally ready to announce that they had found exactly what they were looking for and at a level stronger than expected. "Honestly, I had mentally prepared myself to continue this search for decades, drilling down to lower and lower signal levels and maybe never seeing B-modes from inflation," says Bock.

As Filippini puts it, "There was a finish line. We were trying to get there as fast as possible. We just didn't realize that the finish line was closer than we thought."

"Probably the most serious remaining concern," says Bock, "is that we are seeing polarized emission from our own galaxy. We have tight constraints against this because the spectrum of the CMB is different from that of the galaxy, but we recently installed two new telescopes in the Keck Array, observing at a different wavelength than BICEP2. These detectors are already reporting back data, and we expect they will improve our constraints on the spectrum still further."

News will also be available shortly from the Planck satellite mission, which used high-performance versions of the spiderweb bolometers developed for BOOMERanG and BICEP1. Planck has measured the whole sky at multiple wavelengths to search for the same signal.

There are many B-mode competitors out there that will test BICEP2's finding. Although BICEP pioneered the search for inflationary B-mode polarization, many other cosmologists joined the quest in the intervening years with their own experiments. "There are now about a dozen dedicated ground-based and balloon-borne CMB experiments under way," says Bock. "It has been quite a horse race.



BICEP2 team members lift a liquid helium cryostat to the second floor of the Dark Sector Laboratory to chill the telescope to a temperature near absolute zero.

We're looking forward to hearing the results from these experiments, and of course we are working as hard as we can on our own balloon experiment, Spider."

The Future of Observational Cosmology

It is hard to overstate the significance of BICEP2's findings. In the *New York Times*, Kamionkowski called BICEP2's findings "huge, as big as it gets."

The BICEP2 findings strongly support the theory of inflation (as opposed to non-inflationary cosmologies). Furthermore, only particular models of inflation can account for the abundance of gravitational waves found in the B-modes. So far the simplest models of inflation that were developed by Alan Guth and Andrei Linde match the data.

Primordial gravitational waves are very faint, but with an advanced gravitational-wave interferometer—a futuristic descendant of the Laser Interferometer Gravitational-Wave Observatory, or LIGO (see "Reflections in Research," page 20)—they might actually be detected one day as they pass by Earth.

"It is mind-boggling that we can infer anything about the very instant of the birth of our universe nearly 14 billion years ago," says Bock. "The process that produced the polarization involves physics we don't understand and energies beyond the standard model in particle physics. The primordial gravitational waves were born from quantum fluctuations that were expanded by inflation due to a connection between gravitation—in Einstein's theory of general relativity—and quantum mechanics. This is just the beginning for understanding the exotic physics powering inflation.

"Most of all," Bock continues, "it is amazing to me that our little band of intrepid scientists, students, postdocs—all of whom I consider colleagues and friends—could build a machine that could actually tell us about the birth of the universe." e&s

Jamie Bock is a professor of physics at Caltech and a senior research scientist at JPL.

WHAT BICEP FOUND

BY SEAN CARROLL

The discovery by the BICEP2 experiment of the imprints of gravitational waves on the cosmic microwave background radiation is a historic moment for cosmologists. For the first time, we've directly learned something about the state of the universe one trillionth of a trillionth of a trillionth of a second after the Big Bang.

The result is a great example of the interplay of theory and experiment. Over 30 years ago, Alan Guth of MIT and others formulated the theory of cosmic inflation. In this model, the very early universe underwent a brief period of superfast expansion. That expansion works to smooth out the distribution of matter and energy through space, much like tugging on the edges of a bed sheet will smooth out any wrinkles. Unlike a bed sheet, however, the early universe is governed by the rules of quantum mechanics. And quantum mechanics says that we can't make anything *perfectly* smooth; there will always be some irreducible fluctuations from place to place.

According to inflation, quantum fluctuations are responsible for the tiny deviations in the density of matter that eventually grew into galaxies and clusters in the current universe. The cosmic microwave background, leftover radiation from the Big Bang, displays the influence of those deviations by having a slightly different temperature at different points in the sky. We have seen these temperature differences; what we haven't been sure about is whether inflation is the right theory to account for them. The temperature fluctuations match the prediction of inflation, but maybe there are other theories that would produce the same signature.

Fortunately, inflation makes an additional prediction: not only should the density of matter fluctuate, so should the gravitational field itself. Inflation, in other words, predicts a specific pattern of gravitational waves, which should leave a distinctive imprint on the microwave background. Seeing those waves would be strong evidence that inflation is on the right track.

And that's exactly what BICEP2 has done. In addition to measuring the temperature of the microwave background, the instrument also measured its polarization. Luckily for cosmologists, gravitational waves push and pull on the plasma of the early universe to produce a very particular kind of polarization pattern (the so-called B-modes). BICEP2 was designed to look for this signal, and it found precisely that.

The finding is noteworthy not only because it's a scientific and technological tour de force (although it is that), but also because the gravitational waves were actually relatively easy to find. Inflation predicts a particular pattern, but the overall amplitude of the signal is a free parameter—one that, according to BICEP2, turns out to be just about as big as it could be. That's very good news indeed for cosmologists, as it implies that inflation happened very quickly after the Big Bang. The scientists on BICEP2 have brought us quite a bit closer to understanding how our universe began.

Sean Carroll is a senior research associate in physics at Caltech and the author of From Eternity to Here: The Quest for the Ultimate Theory of Time *(Dutton, 2010) and* The Particle at the End of the Universe: How the Hunt for the Higgs Boson Leads Us to the Edge of a New World *(Dutton, 2012).*

CAPTURING A

It's easy to take maps for granted these days, given the ubiquity of tools like GPS and Google Earth, but for Caltech professor of history Nicolás Wey Gómez, a good map is more than a tool—it's an important artifact that captures and reflects the geographical view of the world from a particular moment in history, providing a potential treasure trove of information.

Take the terrestrial globe shown here, which dates to 1492. The oldest known extant globe, historians believe it portrays the world much as Christopher Columbus would have conceptualized it just before he "sailed the ocean blue."

In fact, says Wey Gómez, "it shows some of the same miscalculations that Columbus made." For instance, it overextends the longitudinal reach of the three known continents—Europe, Africa, and Asia—so that the western edge of Europe is much closer to the eastern edge of Asia than it should be. In part that's because, by the time of the map's making, Portuguese explorers had already explored much of the west coast of southern Africa, and the northern extent of Greenland was known. With so much land extending in the north-south direction, the reasoning went, land must cover much more of the globe from east to west than previously suspected.

WORLDVIEW

"If the map had been accurate, it would have been a very short distance from the Canaries to Japan, an island Martin Behaim, the globe's creator, located on the tropic of Cancer," says Wey Gómez. "That's why Columbus—on his first Atlantic crossing in search of the Indies—descends to the Canaries, and from there he sails generally due west."

But there is more to this globe than what it suggests about Columbus's view of the world. Wey Gómez has used it, along with letters and other literature, to piece together the story of how and why Behaim created the globe—in large part to establish his qualifications for a proposed (but never funded) westward voyage from the Açores islands to northern China. Such maps provide a window for Wey Gómez onto established ways of thinking about the distribution of terrestrial habitats and life around the world at various times throughout history.

"Maps are truly fascinating. They have enabled humans to see a world that could not really be seen from within their bodies on the ground," says Wey Gómez. "In that sense, maps are not entirely unlike the instruments we use today to perceive and to explore a world that we cannot experience directly through our senses." —*KF*

REFLECTIONS IN RESEARCH

At Caltech, mirrors are used to exploit the properties of light—allowing us to better understand life, matter, and the universe.

by Jessica Stoller-Conrad

You may not realize it, but when you took that one last look in your bathroom mirror this morning, you were casually using an essential research tool.

At their most basic level, mirrors are nothing more than smooth, polished glass with a metallic coating. Together, these simple components provide a reflection: the outgoing light that bounces off the mirror re-creates the initial image made by the incoming light.

Through its ability to reflect light, a mirror provides you with a uniquely accurate account of things that are difficult to see from your human perspective—whether it's a patch of unruly hair on the back of your head or the position of the car that's driving behind you on the freeway. Similarly, mirrors provide researchers at Caltech with a unique perspective into areas of science that might otherwise be unapproachable, giving them a way to peer into the microscopic world, examine the properties of unusual materials, and even search for that most elusive of all ripples in space-time, the gravitational wave.

GRABBING WITH LIGHT

Most introductory physics classes include a crash course in optics—the physics that explains the properties of light and its behavior when it comes into contact with different materials and instruments. As a young student reading through a physics textbook, however, Rob Phillips—now a Caltech biophysicist—had trouble seeing how this aspect of physics would ever connect with his intended research path.

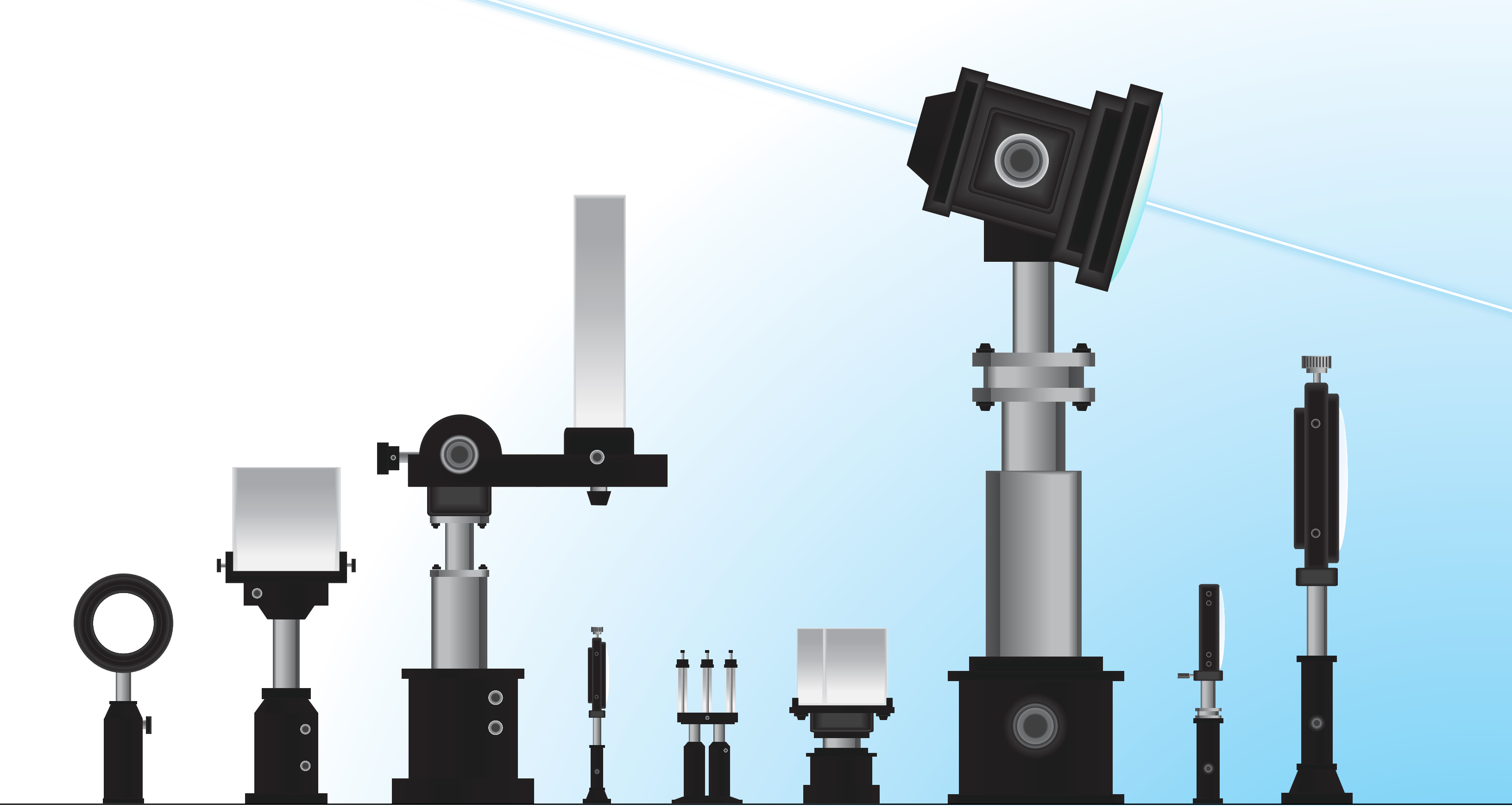
"I studied physics kind of on my own, trying to avoid all parts of the subject that I thought were 'boring' at the time—and that included optics," Phillips says. "Since then, I've come to see that mirrors, lenses, and light are some of the most important tools in all fields of research—from physics to earth sciences, astronomy to biology. They're everywhere."

At Caltech, Phillips's research focuses on understanding how the laws of physics are reflected in the movement and makeup of biological structures, such as cells or DNA. Although theoretical modeling can predict the physical forces that move and control these microscopic building blocks of life, Phillips and his colleagues are able to actually study and quantify those forces by manipulating cells and other tiny structures using a tool known as an optical tweezer.

Rather than trapping objects between two metal pinchers as ordinary tweezers would do—a feat that would be impossible given the microscopic size of Phillips's samples—optical tweezers work by trapping tiny objects with beams of light. And while grabbing, trapping, and moving objects with beams of light might sound more like science fiction than science, optical tweezers are actually a standard tool in physical biology. But how *can* you control an object with light?

"That's not an easy concept to grasp, actually," quips Heun Jin Lee, a staff scientist in Phillips's lab and the group's resident expert on the use of these tweezers.

Lee uses a laser, mirrors, and lenses to harness the properties of light for the manipulation of tiny objects. A laser beam travels along a straight line of light, thanks to the light's steady, unchanging momentum. However, when the light passes through a transparent material, like



a glass lens or water, the light waves propagate at a slower velocity than they did in the air. This change in velocity also causes a change in the light's momentum—which can result in the light's "bent" appearance, the beam changing direction upon reaching the surface of the material.

Since cells are mostly transparent they can act as this refracting—or light-bending—material in an optical tweezer. When the laser beam passes through the cell, the cell bends the light rays, and the light changes momentum—momentum that ultimately transfers from the light to the cell. For example, if you send two light rays from opposite directions at a cell on a microscope stage, the equal but opposite forces of momentum will in essence "trap" the cell in the intersection of the beams, Lee says.

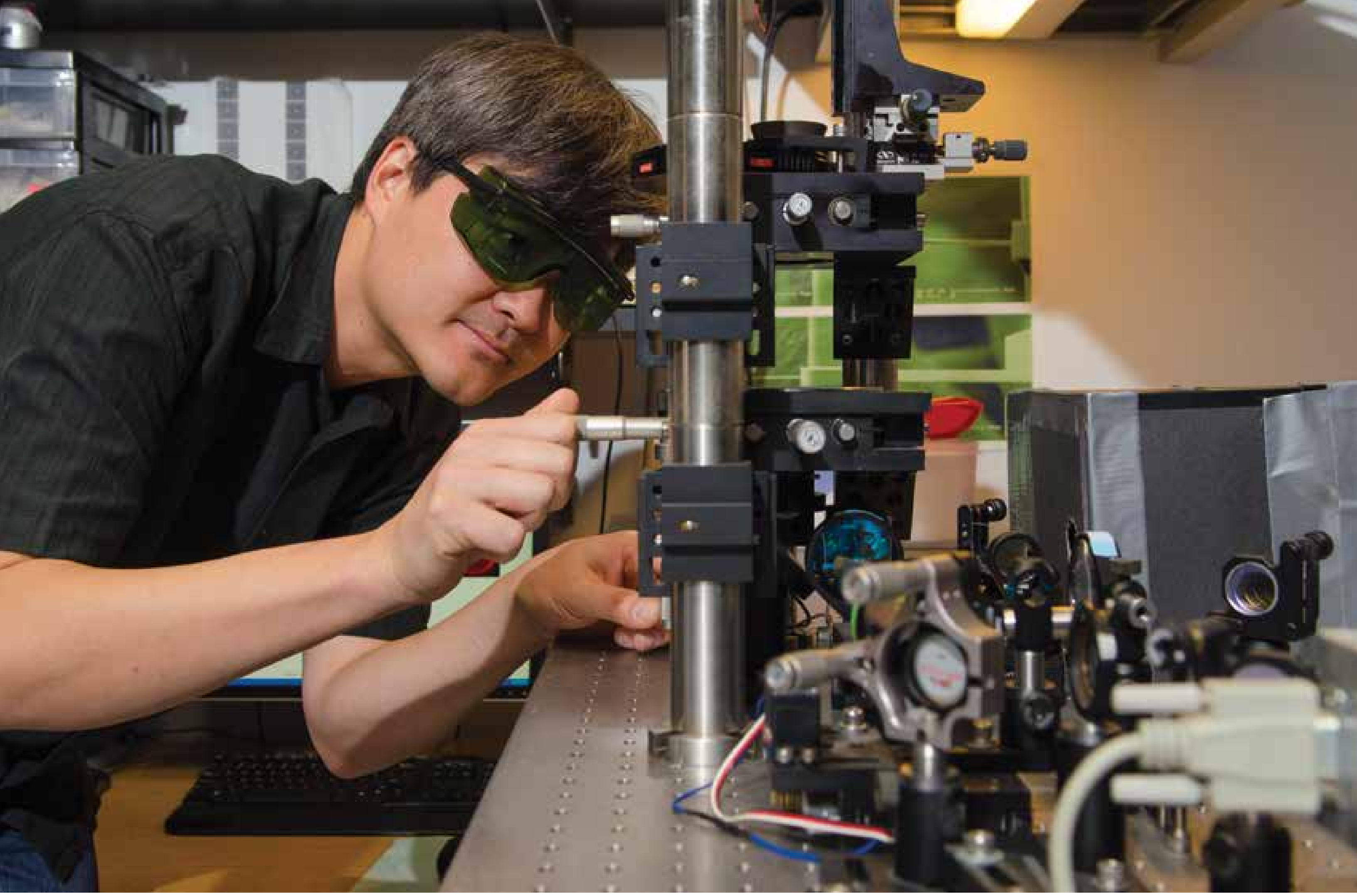
Creating an optical tweezer entails sending parallel rays of light from a laser beam through a series of lenses, each of which refracts—or bends—the rays at carefully calculated angles. Once the bent rays emerge from this optical obstacle course, they encounter a mirror that reflects—or redirects—the light beams onto a biological sample placed on the stage of a microscope. All of this is carefully calibrated so that, when the rays reach the stage, they intersect to form an X—trapping the particle of interest in the center of the X so that it can be held in place, moved around, or manipulated in whatever way the scientists desire.

"Normally when you're watching the microscopic world, stuff moves on its own; you're just an observer. With optical tweezers you're actually able to change things in the environment," says Phillips. "Using a joystick to direct the tweezers, you can capture a particle, hold it, and place it where you want it within three dimensions."

Optical tweezers have allowed Phillips, Lee, and their colleagues to perform a variety of experiments on very tiny objects. They've examined, for example, just how macrophages—cells that gobble up bacteria and cell debris in the bloodstream—prefer to ingest the long, skinny *E. coli* cells they encounter. Using optical tweezers, researchers are able to hand-feed *E. coli* cells to the macrophage in different orientations to observe the differences in the cell's eating habits. As it turns out, they prefer to eat *E. coli* that are approaching end-first; it's more difficult for the macrophage to ingest the bacteria sideways. Enabled by the physical properties of light and mirrors, the tweezers can help researchers gain such insights into how cells interact with objects in their environment.

The tweezers can also be used as a very sensitive device for measuring the force of a single moving cell. "We can capture a swimming *E. coli* and see it try to struggle out of the tweezers, and get a sense of the force that it uses—and match that with the amount of force you would predict," Lee says. If the *E. coli* was using no force at all, it would be perfectly centered in the beam; by measuring the distance between the bacterium and the center of the tweezers' beams, the researchers can determine the amount of force the cell is exerting as it swims. It's as if the *E. coli* were pulling on the basket of a tiny produce scale.

"It's remarkable that we can use these mirrors and microscope objectives—pretty old-fashioned optics—to focus laser light and manipulate microscopic particles," says Lee. "These components have been around for many years—and now we



can use them to capture an *E. coli* cell or tie knots in a strand of DNA. A few decades ago it might have seemed crazy, but now it's just a standard tool."

UNFAITHFUL REFLECTIONS

Mirrors are predictable: when you look at yourself in the mirror, you can expect to see your own reflection, not someone else's. When light encounters a mirror, it faithfully bounces off, looking much the same as it did when it struck—a predictable behavior that falls under a branch of physics called linear optics.

However, materials can also exhibit nonlinear properties that allow an extremely small portion of the reflected light to look different from the incoming light. Physicist David Hsieh takes advantage of these small portions of reflected light to study the arrangement and symmetry of electrons in quantum materials.

Hsieh and his colleagues use a nonlinear optics technique called rotational anisotropy to see how the electrons are arranged within a material. The technique involves shining a laser through a labyrinth of curved and flat mirrors and eventually onto a small crystal made from the material of interest.

"In a typical mirror made of glass, the color of light being reflected is predominantly the color that goes in. But if one looks very carefully, there is a small amount of light reflected at a different color. For example, if you were to shine in red light, you might get some blue out," Hsieh says. "The relationship between the light that goes in and the nonlinear light that comes out tells you something about the way the electrons are arranged within the atoms of the crystal that linear optics would not."

Although the mirror maze isn't

Above: Staff scientist Heun Jin Lee adjusts the alignment of mirrors and lenses in an optical tweezer setup.

directly reporting information about electrons, the experiment would be nearly impossible without mirrors, Hsieh says. "One reason for these mirrors is because our lasers are just monsters," he says. "These instruments weigh hundreds of pounds, so it would be difficult to move them precisely enough to focus the light on a tiny crystal." Instead, the researchers create a path that bounces the light through the maze; by simply changing the angle of the mirrors, they can easily make adjustments to ensure that the laser lands squarely on the crystal.

Mirrors are also needed for another reason: the amount of light streaming from this "monster" laser—capable of providing light for hundreds of experiments at once—is way too powerful to run just a few individual experiments. Instead of using the laser at full strength, which might actually burn the crystal sample, Hsieh says that they use a second kind of mirror, "a sort of 'imperfect' mirror to get rid of some of that light. This mirror reflects some of the laser light, but most of it just goes through the glass. We can let most of the light go through, and take just what we need."

Once the laser beam has been tamped down with mirrors, the researchers can then use a series of lenses to focus the beam onto the crystal. They can then analyze the color of the light reflected off the crystal—and how it differs from the color of the light of the laser. This difference tells Hsieh and his colleagues a lot about how the electrons are collectively arranged around their atoms in the crystal—and how certain electron arrangements are associated with certain properties of the material.

They did this, for example, with crystals from the iridium oxide family of materials, which are known to have both strong electron-electron interactions (a property key to high temperature superconductivity) and equally strong electron-nucleus interactions (a property key to generating topological behavior where the material's surface and its interior act in two completely different ways).

When these two properties combine in the same material—iridium oxides—physicists don't really know what can happen, Hsieh says. The researchers hope that the information they've gathered about iridium oxide's electron symmetry can help device makers exploit the properties of iridium oxide in order to lower the power consumption of electronic devices or to create devices with brand-new functionalities.

"It's only been very recently—in the past few years—that people have recognized this class of materials, like iridium oxides, in which both electron-electron and electron-nucleus interactions are really strong," Hsieh notes. "The mirrors and lasers are essential to our experiments, and our experiments help us learn more about the arrangement of the electrons in these materials—and how these electron arrangements lead to useful properties. Electronics that are more energy efficient are one application of these materials, but no one knows what else this technology is going to bring."

CATCHING THE WAVE

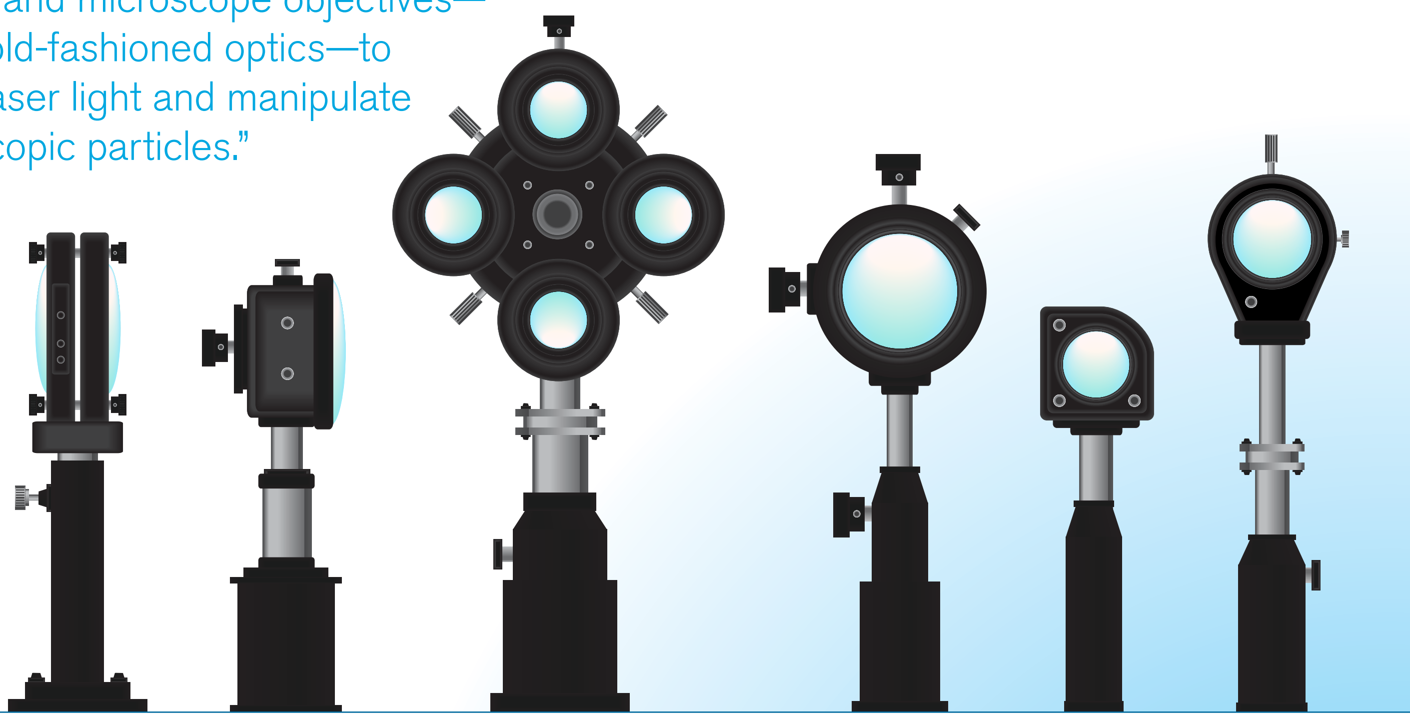
Mirrors that direct a laser beam through a crystal help reveal what's behind the unique properties of various materials. What can mirrors show us when they instead direct two laser beams at one another?

A gravitational wave, says physicist Rana Adhikari. At least, he hopes that will be the case.

Gravitational waves—waves of gravitational force that are thought to create ripples in space-time—result from big cosmic events, like the spiraling merger of two stars or the collapse of large dying stars into a black hole. Although Albert Einstein's 1916 theory of general relativity predicts the waves, and researchers have seen evidence that supports their existence, they have yet to directly detect even a single gravitational wave.

Adhikari is hoping to change all of that by making improvements to the gravitational-wave detector at the Laser

"It's remarkable that we can use these mirrors and microscope objectives—pretty old-fashioned optics—to focus laser light and manipulate microscopic particles."



Interferometer Gravitational-Wave Observatory (LIGO)—improvements that depend on better and more precise mirrors. The LIGO facilities include gravitational-wave observatories operated by Caltech and MIT in Hanford, Washington, and Livingston, Louisiana, that began operations to detect gravitational waves in 2002. Experiments at both observatories ended in 2010 without any definitive sightings, but Adhikari and his colleagues—now armed with the best mirrors and lasers in the world—are working on an even more sensitive detector, called Advanced LIGO, that is slated to begin observations in 2015.

The laser interferometer that is the core of the LIGO observatories is the tool of choice for detecting gravitational waves. The detectors operate on the principle of interference in light waves. If two light waves with identical frequencies and amplitudes—such as waves split from the same laser—interact with one another, and the peaks and troughs of one wave are exactly aligned with those of the second wave, those two waves will combine into one big wave, with four times the energy of the initial wave. However, if the peak of one wave is aligned with the trough of the second wave, the two waves will cancel each other out, resulting in a net energy of zero.

It is this kind of alignment that's at the heart of the LIGO experiment, which involves identical, perfectly aligned waves of laser light that interact within the interferometer, which is an L-shaped tunnel with two 4-kilometer-long arms. A beam of laser light is split at the intersection of the arms, with each half sent down one of the paths. At the end of each arm is a mirror, which bounces the light back to that same intersecting point, near the beam's origin.

If the arms are exactly the same length—and nothing has affected the laser's path—the light from the two beams will interfere with one another, canceling each other out. "If you look at the output, there's nothing—it's totally dark," says Adhikari.

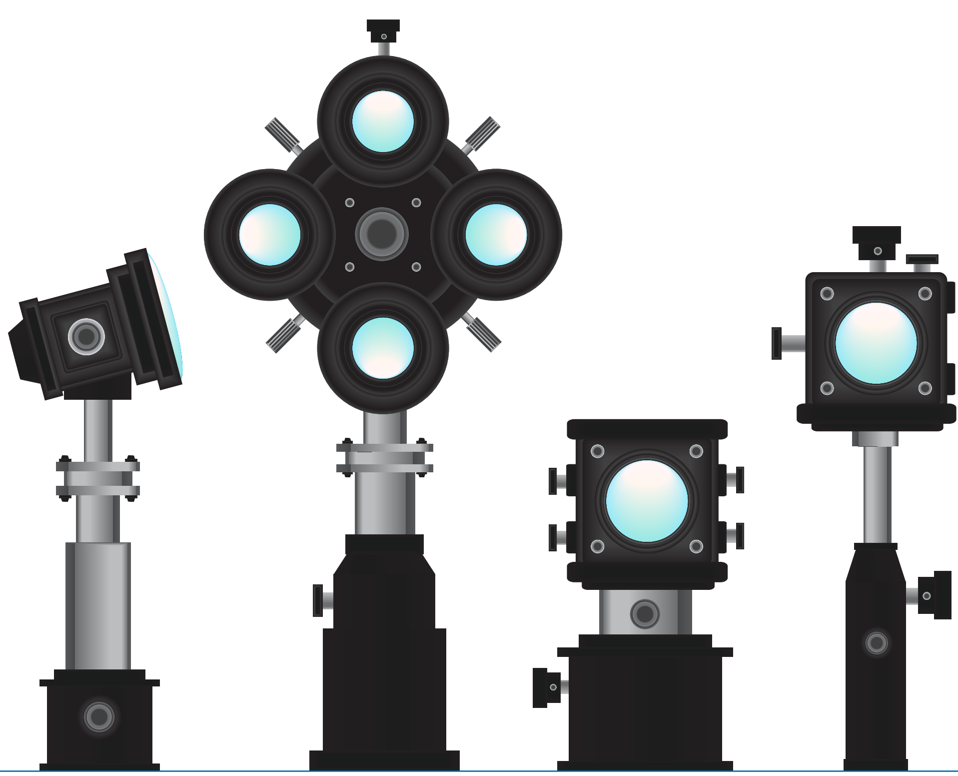
But, if something interferes with the path of the laser beam, the beams will no longer cancel out, and the changes to the resulting light will be detected. To prevent the mirrors from contributing to gravitational-wave false alarms, the arms of LIGO are actually long vacuum tubes, and the mirrors are insulated from vibrations via glass-fiber suspensions. Because geological activity, man-made activity, and even tumbleweeds blowing around outside the observatory could produce a false signal, LIGO also includes many other types of detectors that allow the scientists to subtract alternative possible causes of interference when they are detected. That way, when and if LIGO detects a gravitational wave, researchers will be sure it is indeed a gravitational wave—and not something else.

Right: Betsy Weaver, a detector engineer at Advanced LIGO in Washington, paints a polymer cleaning solution on the surface of the mirror; the polymer is used not only to clean the surface of the mirror, but also to protect the face of the optic from damage during handling.

Interferometers have been used in research for more than a century—since first being developed by Nobel Prize-winning physicist Albert Abraham Michelson in the late 19th century. Although LIGO and Advanced LIGO use the same basic principles, science has made a lot of improvements since Michelson's time, Adhikari says.

"Michelson's device was only a couple of meters long, and the light would only bounce back and forth several times—the Advanced LIGO tubes are 4 kilometers long, so we effectively bounce the light about 200 times in each arm," he explains. Since each of the laser beams essentially travels 800 kilometers, there is more of an effect when a gravitational wave comes through and a greater likelihood that the detectors will sense a change in the beam's path. "That makes us extremely sensitive to even the smallest shifts—and thus, more sensitive to gravitational waves," says Adhikari.

Just how sensitive do these detectors need to be? "To catch a gravitational wave, we're trying to measure a back-and-forth motion that is approximately 10^{-19} meters in length," he says. "What does that even



look like? The wavelength of light is 10^{-6} meters, and the thickness of my hair is something like 10^{-4} meters. These are the kind of distances we can imagine. But the motion we're wanting to detect is just so much smaller, it's almost *un*imaginable."

Further improving on Michelson's interferometer concept, LIGO and Advanced LIGO are made even more sensitive to gravitational waves by the use of ultrasensitive components. For instance, the mirror coatings used were originally developed by the United States for defense purposes during the Cold War, and are some of the best in the world.

That need for the best and most advanced components applies to the mirrors as well. Because laser beams must bounce back and forth between the Advanced LIGO interferometer's large mirrors—which weigh in at 40 kilograms each—and because the more times this bouncing happens, the more likely the detector will be able to feel the tiny stretching of space-time that would represent a gravitational wave, the mirrors must be among the smoothest ever made.

"In our first-generation LIGO detector we had pretty good mirrors, polished with the standard abrasives, but we wanted the best for Advanced LIGO, so we went with this company that is famous for doing telescope optics, called Tinsley," says Adhikari. "They measure the flatness of the mirror with an extremely good interferometer, and if it's a little bit curvy, they shoot it with this particle beam and they knock single atoms off the surface until the mirror gets flatter. It takes a long time, and they are expensive optics, but they will be the best in the world."

Now *there's* a mirror that might have caught the attention of a young Rob Phillips as he was leafing through a dry physics textbook.

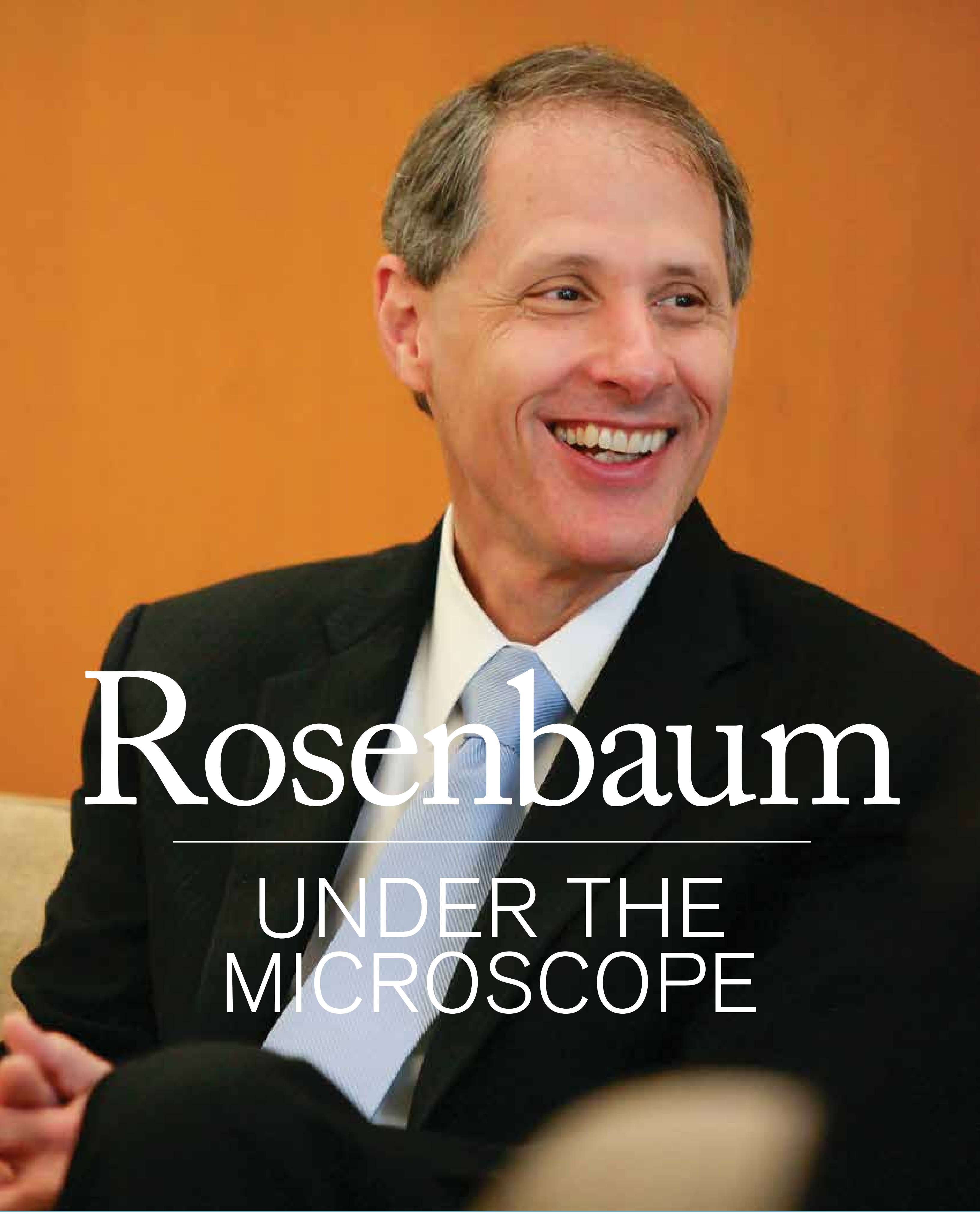
"I may have thought it was boring to learn about at the time, but I was completely wrong," Phillips admits. "Optics is one of the main reasons I switched from physics to biology and, in my view now, it's one of the coolest things in science." e&s

Rana Adhikari is a professor of physics. His work on LIGO is funded by the National Science Foundation.

David Hsieh is an assistant professor of physics. His work is funded by the Department of Energy, the Department of Defense, the Army Research Office, and the Caltech Institute for Quantum Information and Matter.

Heun Jin Lee is a staff scientist.

Rob Phillips is the Fred and Nancy Morris Professor of Biophysics and Biology. His work is funded by the National Institutes of Health.



Rosenbaum

UNDER THE MICROSCOPE

On July 1, Thomas Rosenbaum will take office as the ninth president in Caltech's history after more than 30 years at the University of Chicago—first as a physicist and faculty member; next as director of its Materials Research Laboratory and, later, its interdisciplinary James Franck Institute; then as vice president for research and for Argonne National Laboratory; and, ultimately, as the university's provost. In anticipation of Rosenbaum's arrival, *E&S* asked him to sit down and answer a few questions on topics ranging from diversity to Caltech's future to his summer reading list. Here, then, is a brief but close-up look at our next president.

***E&S:* UChicago is a pioneer in diversity. What did you learn through the process of expanding diversity that may be applicable at Caltech?**

Rosenbaum: Diversity is integral to the values and success of Caltech; it is not an add-on. Universities are in the essential business of attracting the most original, creative, and compelling scholars and creating an environment of unflinching inquiry and challenge. These aspects of academic eminence require faculty, students, and staff from a wide range of backgrounds and with diverse perspectives.

What do you think distinguishes Caltech in higher education?

Caltech's combination of absolute excellence, traversable disciplinary barriers, and soaring ambition is simply remarkable. It does not seem possible that a university with only 300 faculty members and 2,250 undergraduates and graduate students combined could be setting the intellectual agendas and running world-preeminent facilities in so many different scientific and engineering arenas, yet we are. JPL is a huge and essential multiplier, but in my view it fundamentally comes down to Caltech's culture of fearlessness.

What do you think is the biggest challenge before higher education today?

Segmentation, exacerbated by a background environment of disinvestment. Private research universities like Caltech provide a very special residential experience where education and research are intertwined, but they can only serve a small segment of the student population and are squeezed by declining federal investment in research. Publicly funded institutions traditionally have provided the means for a larger body of students to receive an education, with some exemplar research universities among the mix, but states are rapidly retreating from this element of the American dream. Liberal arts colleges are highly tuition dependent and not all will be able to stay in business. For years these different parts of the higher-education spectrum, of distinct character but linked purpose, have provided a range of opportunities for students. I fear that the spectrum is segmenting and leaving large gaps between the elements.

When you consider where Caltech could be decades and decades into its future, what are your hopes?

We need to continue to be a place of possibility, for the intellectual dreams of our faculty and students and alums, and for the aspirations of the world at large.

Tell us something that people would be surprised to know about you.

I spent every spare minute I had in high school playing basketball. The hoop on the president's house garage sealed my move to Pasadena!

What talent would you love to have that you don't?

I wish I could carry a tune. I love music, but everyone is happier if I just drum my fingers or tap my feet.

What's on your summer reading list?

To catch up with the eight or so issues of the *New Yorker* that I am (perpetually) behind!

What words do you live by?

There is a Jewish teaching that in one pocket you should put a slip of paper that says "For me the world was created," and in another pocket you should put a slip of paper that says "I am but dust and ashes." The secret of a successful life is to know when to reach into the proper pocket. e&s

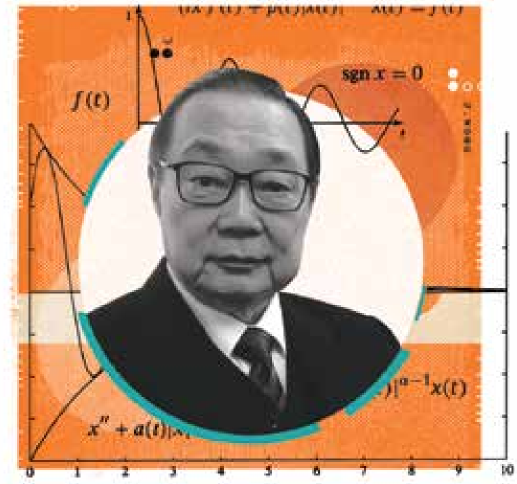
Presenting the 2014 Caltech Distinguished Alumni

On May 17, Caltech recognized six of its graduates with the Distinguished Alumni Award, the highest honor the Institute bestows on its alumni. This year's recipients highlight the breadth of fields in which Caltech graduates have gone on to become leaders—ranging from cosmology to higher education, and from aerospace to biomedicine.

First presented in 1966, the award recognizes a particular achievement of noteworthy value, a series of such achievements, or a career of noteworthy accomplishment.

Read more about each Distinguished Alumnus at *alumni.caltech.edu/daa.*

Alumni stories provided by the Caltech Alumni Association. For more about these stories and to read about other alumni in the news, go to *alumni.caltech.edu*.

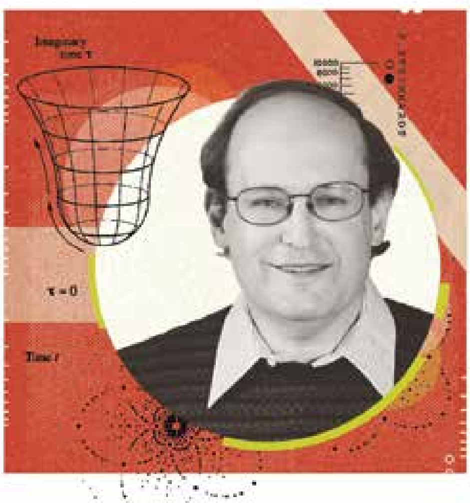


James S. W. Wong (PhD '65)
Chairman, Chinney Holdings Ltd.
Honorary Professor of Mathematics, University of Hong Kong
For substantial contributions in mathematics and commercial enterprise. Wong's extensive scholarly research has focused on oscillation theory of differential equations. As an entrepreneur, he transformed his family business into a leading international investment company.

"My philosophy in business, academia, and in life, rests on three foundations: truth, fairness, and freedom. I have been fortunate in that they have served me well."

Mary Baker (MS '67, PhD '72)
President, ATA Engineering Inc.
For pioneering entrepreneurship and leadership in aerospace. Baker founded ATA Engineering Inc., a prominent, employee-owned provider of analysis and test-driven design solutions for mechanical and aerospace systems.

"Everyone contributes to and shares in the success of our company. We feel that our process makes for the best science, and the best business."



Paul J. Steinhardt (BS ’74)
Albert Einstein Professor in Science, and Director of the Princeton Center for Theoretical Science, Princeton University

For seminal contributions to theoretical physics and cosmology. Among his many achievements, Steinhardt developed new inflationary models of the universe, advanced the theory of quasicrystals, and discovered the only known naturally occurring quasicrystals.

“I’m very optimistic about the future of science. . . . New experimental technologies, new discoveries, new ways of teaching and sharing information—these are all the earmarks of exciting times.”

Richard K. Miller (PhD ’76)
President, Olin College of Engineering
For visionary leadership and commitment to innovation in engineering education for the benefit of society. As the founding president of Olin College, Miller led the creation of a new institution recognized for its unique teaching methods and models.

“We believe that Olin’s approach is an effective complement to other time-tested methods of engineering education. We see this not just as a college—but a cause.”

Richard H. Scheller (PhD ’80)
Executive Vice President, Research and Early Development, Genentech
For seminal work and leadership in biological sciences. Among his many achievements, Scheller identified mechanisms of neurotransmitter release. Now at Genentech, he oversees the development of basic research into new treatments for human disease.

“It’s an extremely exciting time in medicine. To unblind a trial and see cancer patients live longer because of your medicine is a pretty rewarding endeavor.”

David E. Chavez (BS ’96)
Principal Investigator and Project Leader, Los Alamos National Laboratory
For his extensive and groundbreaking contributions to chemistry. Chavez created versatile new synthetic compounds and processes that advanced the development of high-nitrogen energetic materials, which are now being used for applications in a wide variety of fields.

“Synthesizing new molecules has an artistic quality to it. You can shape atoms into arrangements never before seen in nature.”

A NEW FOCUS FOR THE TOLMAN-BACHER HOUSE

by Kimm Fesenmaier

The on-campus house where Caltech chemist and mathematical physicist Richard Tolman once conversed with such eminent scientists as Albert Einstein and Robert Oppenheimer has been spruced up and repurposed as the new home of the Keck Institute for Space Studies (KISS).

With support from the W. M. Keck Foundation, the Tolman-Bacher House, a single-family home located northeast of the Beckman Institute, was recently renovated to provide KISS with office space and small meeting rooms while maintaining the historical integrity of the original 1920s home. A second, complementary building (top) has been constructed to the west of the house and accommodates a large conference room.

The entire complex, dubbed the Keck Center, will provide a central location for KISS workshops, symposia, and idea-stimulating activities, with the conference building also serving as a meeting place for Caltech's Board of Trustees.

"We are so thankful for the generosity of the W. M. Keck Foundation," says Tom Prince, professor of physics and director of KISS. "This new facility will enable KISS to continue to bring together groups of scientists and engineers from diverse backgrounds to attack the most exciting problems in space science and engineering."

Lance E. Davis 1928–2014

Lance E. Davis, the Mary Stillman Harkness Professor of Social Science, Emeritus, passed away on Monday, January 20. He was 85 years old.

Davis, whose research focused on the economic history of financial markets and institutional and technological change, received his undergraduate degree from the University of Washington in 1950 and, after serving in the Navy during the Korean War, earned his doctorate from Johns Hopkins University in 1956. He came to Caltech from Purdue University in 1968 and was a professor of economics until 1980, when he was named Harkness Professor. He retired in 2005.

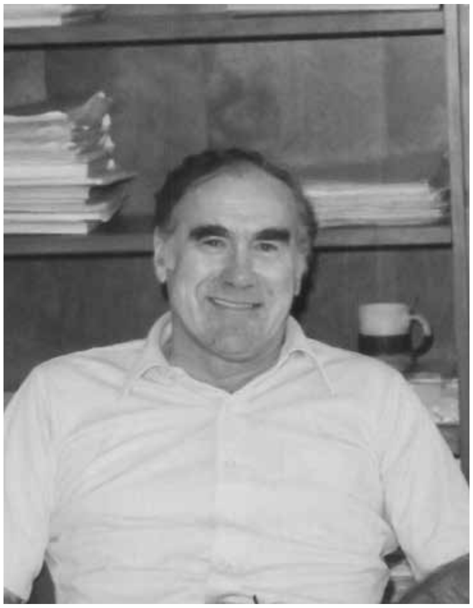
Davis played a key role in the development of the social science program at Caltech and was the executive officer for the social sciences from 1982 to 1985. He was a fellow of the American Academy of Arts and Sciences.

Gerald B. Whitham 1927–2014

Gerald B. Whitham, the Charles Lee Powell Professor of Applied Mathematics, Emeritus, passed away on Sunday, January 26. He was 86 years old.

Whitham, a pioneer in the area of nonlinear waves whose research focused on fluid dynamics and the study of wave phenomena, including sonic booms, supersonic flow and shock-wave dynamics, and ocean waves, received his BSc in 1948, MSc in 1949, and PhD in 1953, all from the University of Manchester. He came to Caltech in 1961 as a visiting professor of applied mathematics, was a professor of aeronautics and mathematics from 1962 to 1967, a professor of applied mathematics from 1967 to 1983, and the Powell Professor until his retirement in 1998.

Whitham was instrumental in setting up Caltech's applied mathematics program in 1962, and served as the executive officer for applied mathematics from 1971 to 1980. He was a fellow of both the American Academy of Arts and Sciences and the Royal Society of London.



INFLUENTIAL PHRASES We posed the question "What words do you live by?" to Caltech's new president, Thomas Rosenbaum (see page 26), and to our alumni. Here's what some of them had to say.

The **TRUTH** shall make you free.

—Caltech motto

Against **THE ASSAULT OF LAUGHTER** nothing can stand.

—Mark Twain

The answer **pre-exists**. It is the question that must be **discovered**.

—Jonas Salk

Practice makes better.

If it scares you, ***DO IT***.

Don't worry, the pants will be **ready** on time.

—my tailor

Don't always **BELIEVE** what you **THINK**.

The polhode **ROLLS WITHOUT SLIPPING** on the herpolhode lying in the invariable plane.

—Classical Mechanics

Man is the **tool-using animal**.

Reality is **that which**, when you stop believing in it, **doesn't go away**.

—Philip K. Dick

Always follow the Golden Rule, always say please and thank you, **AND ALWAYS USE YOUR TURN SIGNAL**.

A one-on-one session can be invaluable in planning for your future.

Let one of our experienced consultants help you through the intricacies of retirement planning. Get guidance on how to pursue your financial goals.

Call 1-800-732-8353 today to set up an appointment with a TIAA-CREF consultant.

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