e&s

Engineering & Science

VOLUME LXXVI, NUMBER 2, SUMMER 2013

California Institute *of* Technology

Engineering & Science

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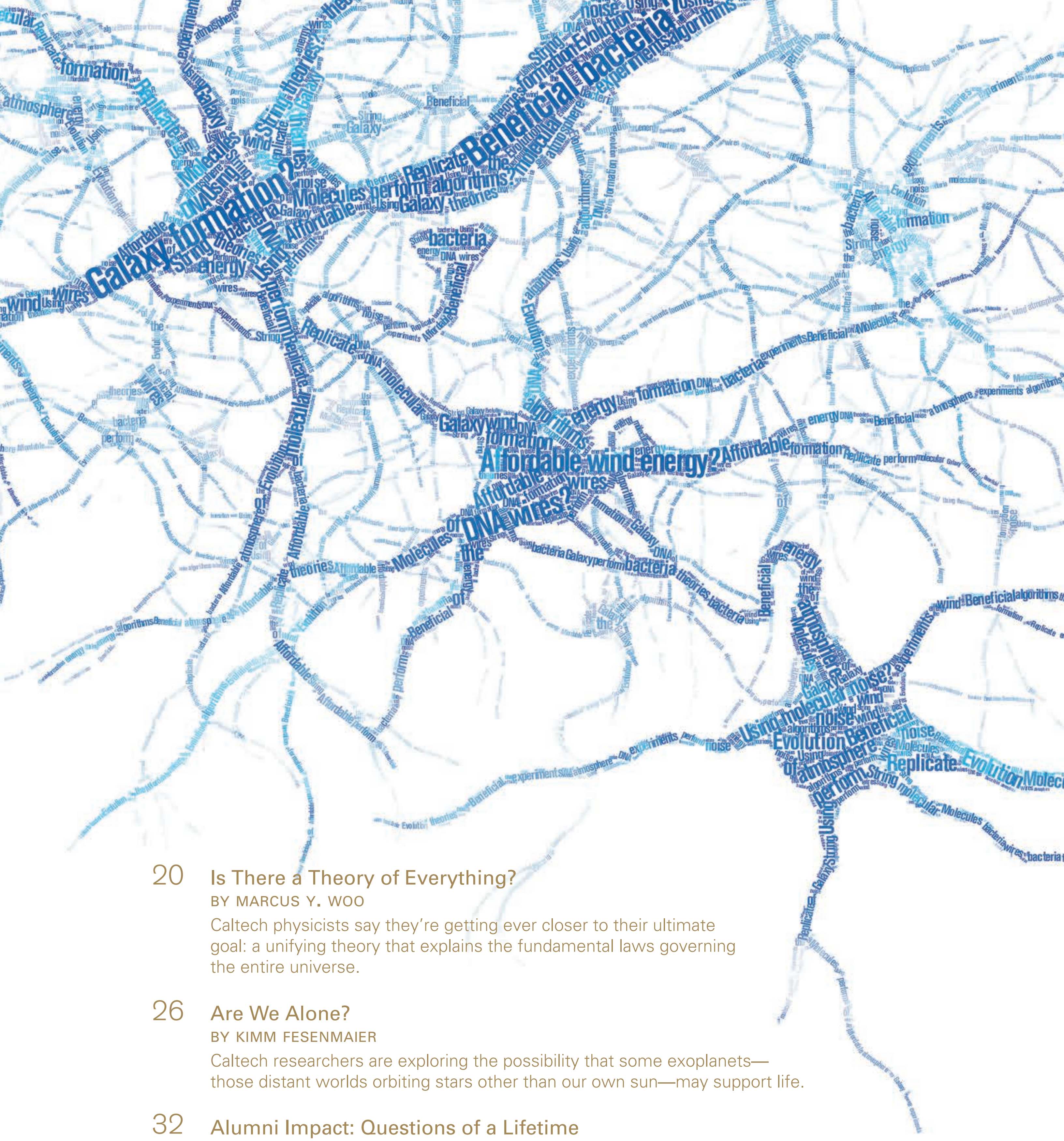

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Caltech on Twitter

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

@PolycrystalhD: Eating lunch with my lab and Stephen Hawking rolls by, just another Thursday @Caltech

@paulajohnson: If the Caltech Space Challenge were televised, it would be called "The Amazing (Space) Race!" @Caltech_SC2012

@joecparrish: Blown away by brilliant students and innovative human mission concepts to Phobos & Deimos @Caltech_SC2012

@rockbot: To this day, every time I hear the Ride of the Valkyries, I get really tense and worry I'm not ready for finals. #caltech

@EspreeDevora: @SimoneMBA Yes @Caltech has incredible talent doesn't it! @techzulu really clued me in on how dynamic the entrepreneurial community is there

@Sam_Neira: Actual rocket scientists are much funnier in person than how they're portrayed on teevee #nasajpl #caltech

@Stephen_Hinkel: TV trucks at Caltech means #earthquake but I must be getting used to living in southern California because I felt nothing

@JannaLevin: One of the many kooky aspects of sabbatical at Caltech: everywhere I go, everyone is talking science. Nuts.

@TheFryGirlInc: Off to @Caltech #Pasadena to make mini donuts for the students' midnight madness breakfast while studying for exams. Late night sugar rush!!!

@preskill: A good way to appreciate the mysteries of quantum mechanics is to teach the subject to sophomores. @caltech

Tweets may have been edited for spelling and grammar.

Engineering & Science

VOLUME LXXVI, NUMBER 2, SUMMER 2013

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Engineering & Science (ISSN 0013-7812) is published quarterly at the California Institute of Technology, 1200 East California Boulevard, Pasadena, CA 91125. Annual subscription $20.00 domestic, $30.00 foreign air mail; single copies $5.00. Send subscriptions to *Engineering & Science*, Caltech Mail Code 5-32, Pasadena, CA 91125. Third-class postage paid at Pasadena, CA. All rights reserved. Reproduction of material contained herein forbidden without authorization. © 2013, California Institute of Technology. Published by Caltech and the Alumni Association. Telephone: 626-395-8371.

Printed by Navigator Cross-Media, Inc., Glendale, California.

PICTURE CREDITS
Cover – photo by Wikimedia Commons (Andrew Horne), illustration by Juan Osborne; Inside front cover, 7 (bottom) – photo by Henning Dalhoff/Science Source, illustration by Juan Osborne; 3, 9 – Bill Youngblood; 4-5, 28-29, 30-31 – NASA/JPL-Caltech; 7 (top) – photo by Lance Hayashida, illustration by Alicia Hardesty; 8 (left) – Elaine Y. Hsiao; 10 (top), 16, 17, 18, 19, 36 – Shutterstock.com; 10 (bottom) – Markus Meister; 11 – Ankur Saxena; 13 – original photo by JupiterImages, globe by iStockPhoto.com, composition by Lance Hayashida; 14, 15 – Lance Hayashida; 20, 25 – Christine Berrie; 23 – Seth Hansen; 24 – Bob Paz; 26 – photo by NASA/JPL-Caltech, illustration by Juan Osborne; 35 – Ta-liang Teng

Commencements

As I prepare to leave Caltech in a few weeks, I am often asked what I am most proud of from my tenure as president. That answer is simple. I'm proud of the entire Caltech community—our students, faculty, staff, alumni, and the many champions who help fuel our dreams. I often reflect on a quote from anthropologist Margret Mead: *"Never doubt that a small group of thoughtful, committed citizens can change the world; indeed, it's the only thing that ever has."*

At Caltech, this is what distinguishes us from the pack: our culture, our collaborative approach to problem solving, and our belief that high-risk ideas can lead to revolutionary transformations in science and society. As the graduating students of 2013 join the Caltech women and men who have influenced the world through science and engineering, I applaud them. They, along with our small but mighty cadre of faculty, alumni, and staff, are what I call action architects—they have the tenacity to never give up, and they walk straight toward the challenges that others run away from.

> "They are what I call action architects—they have the tenacity to never give up, and they walk straight toward the challenges that others run away from."

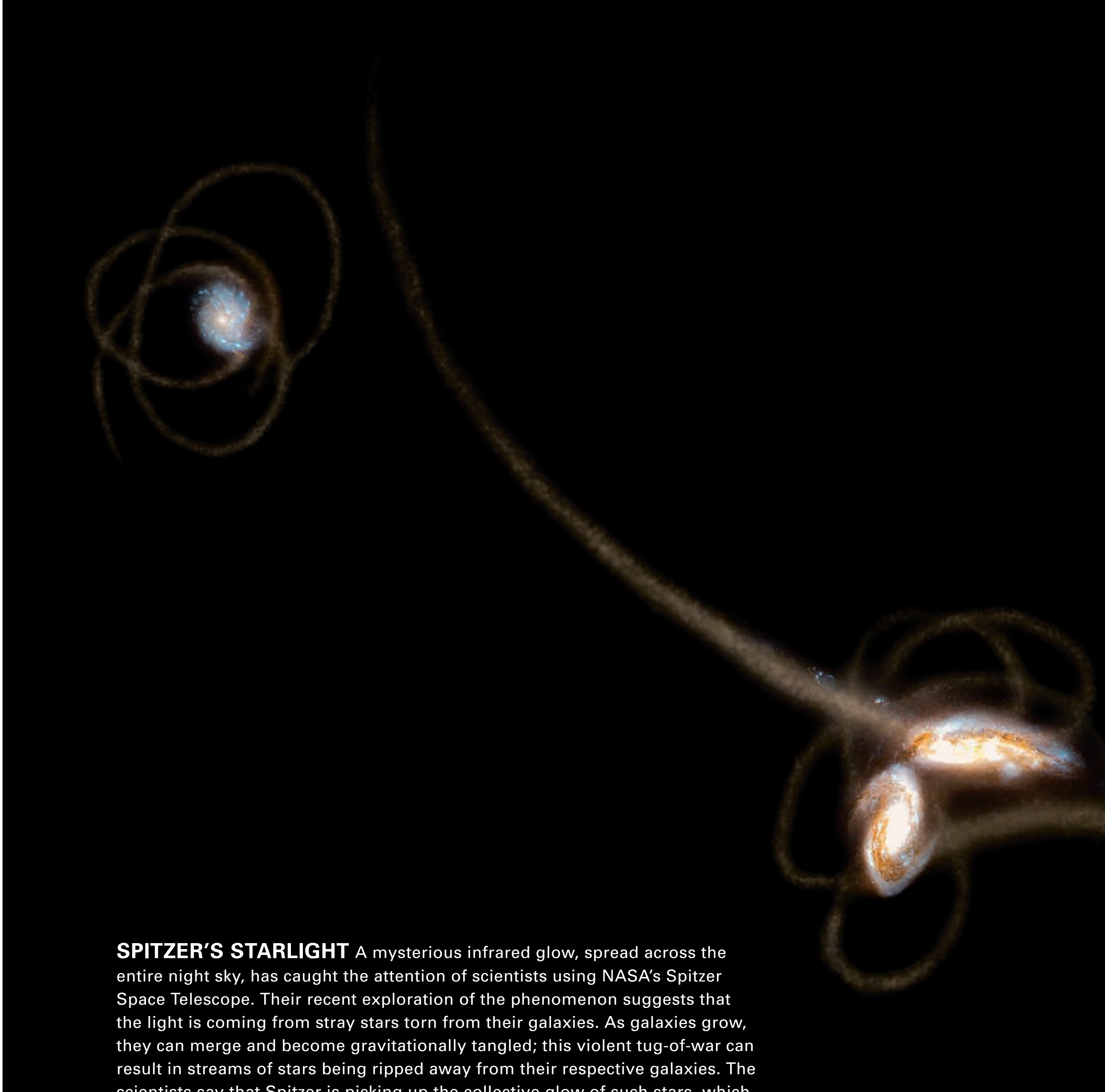
In this issue you'll read about some of the big ideas and questions our people are pursuing. From John Schwarz's pioneering work in string theory to Tom Heaton's advances in earthquake early-warning systems to the exploration of exoplanets in our universe by a group of astronomers—these efforts are offering answers to some of the world's most difficult questions. The creative power behind these research stories defines the Caltech Advantage, in which collaboration drives ideas and risk is an ingredient for success.

I am thankful and grateful to have met so many of you during my time here. Carol and I look back on these seven years as full of excitement, even during our most challenging moments. The Caltech Advantage is everlasting; it existed before we arrived and it will continue to thrive in the future. I take comfort in knowing that, as I leave, Caltech is even better poised to lead the future of scientific and technological discovery and education.

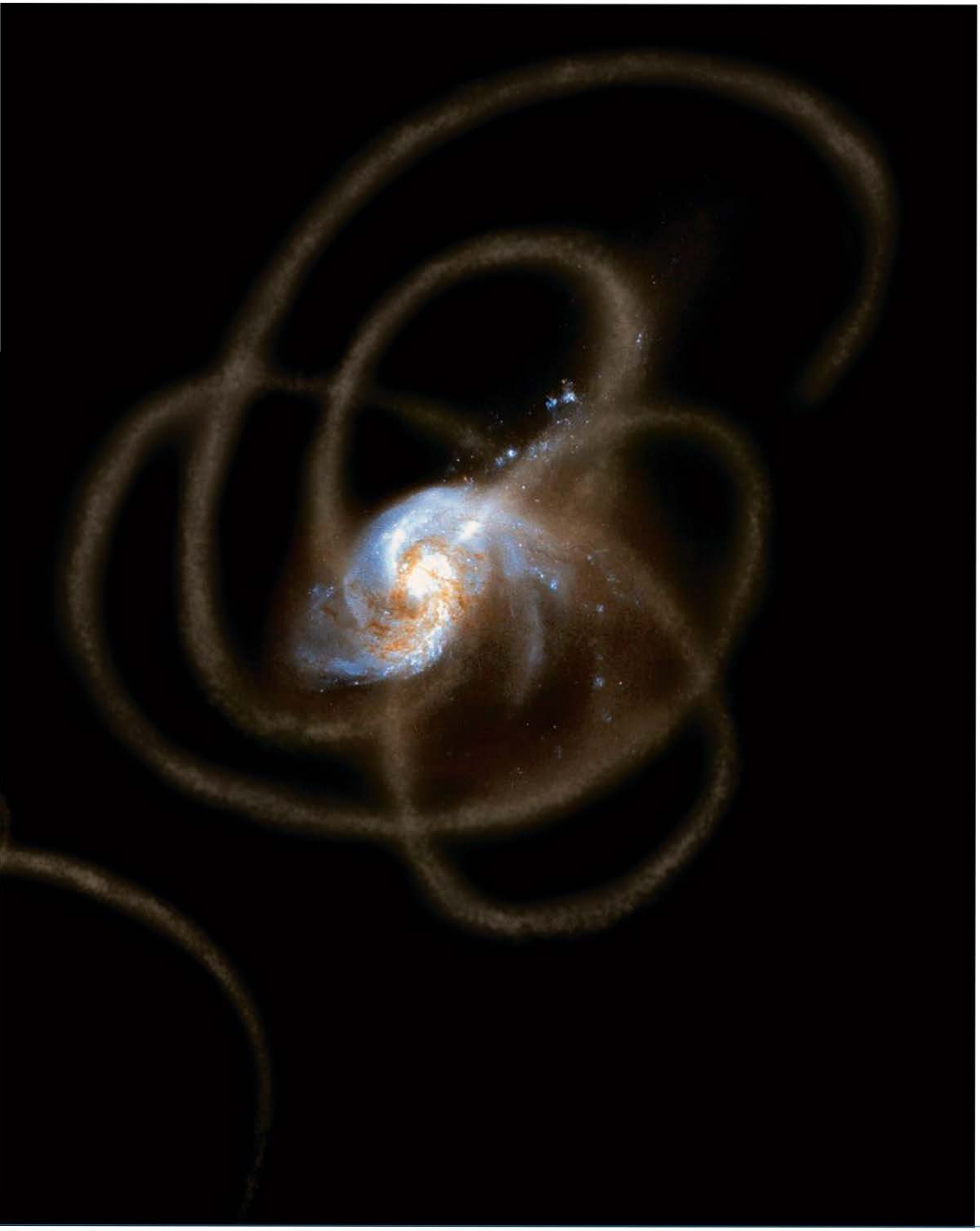
Finally, to our graduates: My hope for each of you is that you will carry your lessons from Caltech into the world. Stay creative, trust your intuition, be a person of action, and walk toward the challenges.

Yours, as always, in discovery,

Random Walk



SPITZER'S STARLIGHT A mysterious infrared glow, spread across the entire night sky, has caught the attention of scientists using NASA's Spitzer Space Telescope. Their recent exploration of the phenomenon suggests that the light is coming from stray stars torn from their galaxies. As galaxies grow, they can merge and become gravitationally tangled; this violent tug-of-war can result in streams of stars being ripped away from their respective galaxies. The scientists say that Spitzer is picking up the collective glow of such stars, which linger in the spaces between galaxies. This artist's concept is adapted, in part, from galaxy images obtained by the NASA/ESA Hubble Space Telescope.



> “We must continue to go into space for the future of humanity. I don’t think we will survive another thousand years without escaping our fragile planet.”
>
> —*Cosmologist Stephen Hawking, speaking to a full house at Beckman Auditorium on April 16, 2013*

Coursera by the Numbers

Coursera is an online learning platform founded in 2011 by Stanford computer-science professors Daphne Koller and Andrew Ng; it uses video presentations, active discussion groups, and interactive exercises to encourage learning and ensure long-term retention of the material. Classes are not for credit. Caltech began offering lessons to students and members of the general public via Coursera in the fall semester of 2012.

DURING THE SPRING SEMESTER OF 2013

62 schools participated

312 classes were offered

70,000+ new students signed up weekly

AT CALTECH

3 professors offered course material on Coursera

110,000+ students enrolled in Caltech offerings

4–10 hours per week were required of students

the cost for enrolling in Caltech offerings **$0**

HTTPS://WWW.COURSERA.ORG

The Drake Equation

In 1961, Frank Drake, then at the National Radio Astronomy Observatory in Green Bank, West Virginia, formulated what has become a famous and eponymous equation that provides a framework for thinking about the factors involved in any estimate of the number of technologically advanced civilizations that might exist in the Milky Way galaxy and perhaps be detectable by us. (For more on the likelihood of life on other planets, see “Are We Alone?” on page 26.)

The number of civilizations in the Milky Way galaxy whose electromagnetic emissions are detectable.

The fraction of those stars with planetary systems.

The fraction of suitable planets on which life actually appears.

The fraction of civilizations that develop a technology that releases detectable signs of their existence into space.

$$N = R^* \cdot f_p \cdot n_e \cdot f_l \cdot f_i \cdot f_c \cdot L$$

The rate of formation of stars suitable for the development of intelligent life.

The number of planets, per solar system, with an environment suitable for life.

The fraction of life-bearing planets on which intelligent life emerges.

The length of time such civilizations release detectable signals into space.

(Source: www.seti.org/drakeequation)

ELEMENTS OF STYLE

Last September, on a cross-country flight, a fashion designer grabbed an open seat next to the director of outreach for the Institute for Quantum Information and Matter at Caltech. The two—Alicia Hardesty and Spiros Michalakis, respectively—hit it off, spending the next five hours talking about math, fashion, education, and how to engage the younger generation.

From the high-altitude meet-up, a collaboration was born: Project X Squared, a clothing line "for the nerd in all of us." Hardesty, well known for her work on season 10 of the fashion reality show *Project Runway*, has been visiting campus regularly, brainstorming with grad students, postdocs, and professors. She was even a speaker at the TEDxYouth@Caltech event for school children back in January.

Project X Squared will link science and street wear, but it is also focused on inspiring interest in art and science, especially in children. "I wanted to find a way to bring the art world to the science world and excite kids," Michalakis says.

And so, even as the collaborators have worked on designing the line's first featured items—including a lab coat that actually fits properly and can be worn as street wear (shown at right on graduate student Crystal Dilworth)—they have also been thinking ahead, planning to use their proceeds for educational outreach efforts. Make it work! —*KF*

For more about Project X Squared, check out their website at http://projectxsquared.com.

Insider Info

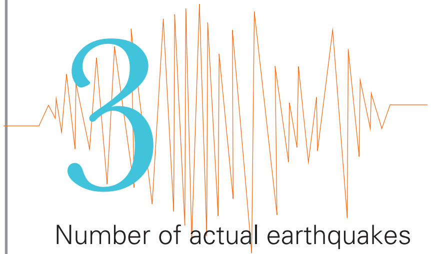
20

we about can change

Number of different words used in the cover image

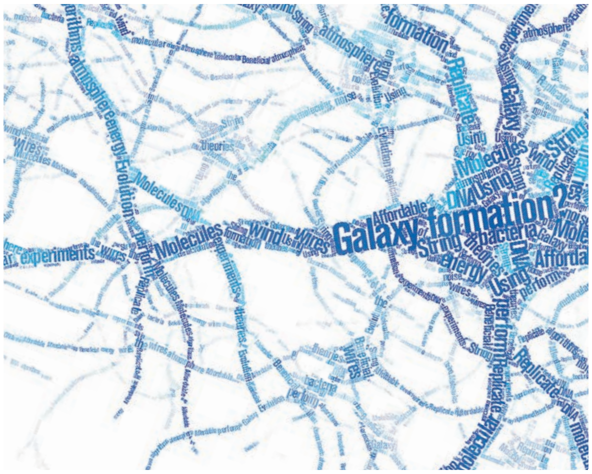
carrot

Top entry on our art director's list of items that should be included in our "theory of everything" illustration (see page 20)



3

Number of actual earthquakes researcher Maren Boese was first warned about by her computer and subsequently felt in her office (see page 12)



MORE BIG QUESTIONS As we were creating our cover's typographic Thinker out of the *big* questions we cover in this issue, we realized that these four questions—while significant and truly big—do not cover the breadth and depth of the scientific and intellectual inquiry that goes on every day at Caltech. And thus was born our Table of Contents page, featuring typographically rendered neurons made up of bits and pieces of the big questions being asked by the Institute's past and current MacArthur fellows—recipients of the so-called genius award—of which there are 11 in all. These scientists are asking questions that range from whether we can use beneficial bacteria from the human gut to harness disease, to how we can program molecules to carry out algorithms, to what processes drive the evolution of Earth's atmosphere, to how we might best obtain inexpensive wind energy.

Just a little extra food for thought.

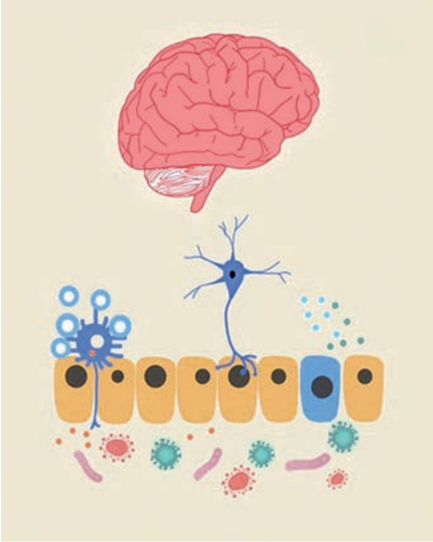
On a bright Southern California day in mid-January, about a thousand people—from scientists to students to members of the community—packed into Beckman Auditorium for a mind-stretching experience at the second TEDxCaltech. The daylong series of talks and performances was part of the program of independently organized events called TEDx, modeled after the popular TED (Technology, Entertainment, and Design) talks—a series of conferences whose motto is "ideas worth spreading."

This year's TEDxCaltech theme, "The Brain," was explored by 25 speakers, who looked at the mind's inner workings, described dramatic new treatments for brain disorders and diseases, explained how we decide what to eat each day, and considered the future of neuroprosthetics, in which mind is fused with machine to help the blind see and the paralyzed walk. Check out these next few pages for a glimpse of what the TEDx attendees heard, saw, and learned. And for even more TEDxCaltech content, you can watch the speakers' presentations at http://tedxcaltech.caltech.edu.

Minding the Microbiome

Postdoctoral scholar Elaine Hsiao (PhD '13) offered up two images side by side during her TEDxCaltech talk: one a bottle of hand sanitizer; the other a child kissing the snout of a large pig.

"I wanted people to consider what we do day to day that changes or disrupts our microbiome," Hsiao says, "and how that might influence our health and predisposition to disease."



A microbiome is a collection of microbial organisms that live in a particular environment—the human body, for example. During TEDxCaltech, Hsiao provided a brief overview of how a microbiome interacts with its environment and beyond, looking specifically at the mechanisms by which gut microbes can affect the brain and at findings that have shown that changing the composition of the microbiome can alter complex behaviors such as anxiety and learning and memory, as well as disease.

As one example, Hsiao described a microbe-based treatment for autism-like symptoms in mice, a treatment she helped develop alongside Caltech biologists Sarkis Mazmanian and Paul Patterson.

"What if we could—without a single invasive procedure—treat disorders like autism, depression, and multiple sclerosis?" Hsiao asked. "Microbe-based therapeutics might offer a way to . . . impart long-lasting effects without the need for a continuous treatment." —*KF*

Fruit Fly Feelings

Most people think of fruit flies only as annoying pests that invade our kitchens and cause us distress. But it turns out flies have feelings, too—and may hold clues to understanding how the human brain processes emotion.

In the lab of Caltech biologist David Anderson, *Drosophila*—the common fruit fly—has served as an important model for unraveling the functions of various genes and their roles in influencing behavior.

"Usually when people think about emotion, they assume it's really complicated and something that only humans have," says Hidehiko Inagaki, a graduate student who came to Caltech from Tokyo to work in Anderson's lab. "But when we compare a number of emotion-related genes in the fly to those in humans, they are quite similar."

Inagaki and junior neurobiology student Ketaki Panse spoke at TEDxCaltech about their research, which looks at neuromodulators—chemicals like dopamine and serotonin that can tamp down or boost brain signals—that might be responsible for "emotions" brought on by hunger in fruit flies. These emotions are what prompt the flies' feeding and searching behaviors.

"There are so many genetic tools that we can use with the fruit flies, since they only have four chromosomes and are obviously much simpler organisms than we are," explains Panse. "If we can understand this simple organism, then hopefully we can understand the fundamental mechanisms that underlie both basic fly emotions and complex emotions in humans, which I think is really cool."—*KN*

About Faces *Doris Tsao, assistant professor of biology, is one of the many Caltech faculty members and students who presented their brain-related work at TEDxCaltech. Faced with the challenge of summing up their research in short presentations, participants used videos, illustrations, photographs, and even a bit of humor to provide a snapshot of their work. Here, Tsao shows how neurons respond to faces; the work is from an experiment that explored object perception in the brain.*

> "This is an organ of surreal complexity, and we are just beginning to understand how to even study it."
>
> —*Thomas Insel, director of the National Institute of Mental Health, on the brain*

CRIB SHEET: BRAINY WORDS

con•nec•tom•ics

A field in which the goal is to map an organism's neural circuits or its entire nervous system; such a map is called a connectome.

op•to•gen•et•ics

A technique by which neurons are genetically engineered to produce a class of protein called opsins; the opsins allow those neurons to be excited or inhibited when light strikes them. The method lets scientists use a laser to control, in real time, individual neurons in a living brain.

neu•ro•e•co•nom•ics

The study of how the brain works when making value-based decisions.

THE HUMAN BRAIN...

has approximately

100

billion neurons

weighs an average of

1,500

grams

(about 3.3 pounds)

has over

100

trillion synapses

takes

200

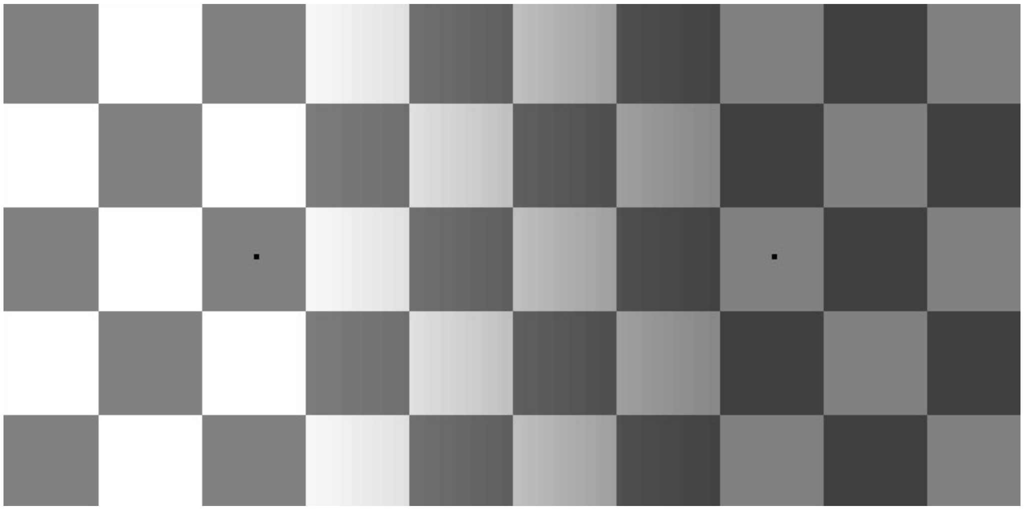
milliseconds to choose which of two foods to eat

What's in a Song?

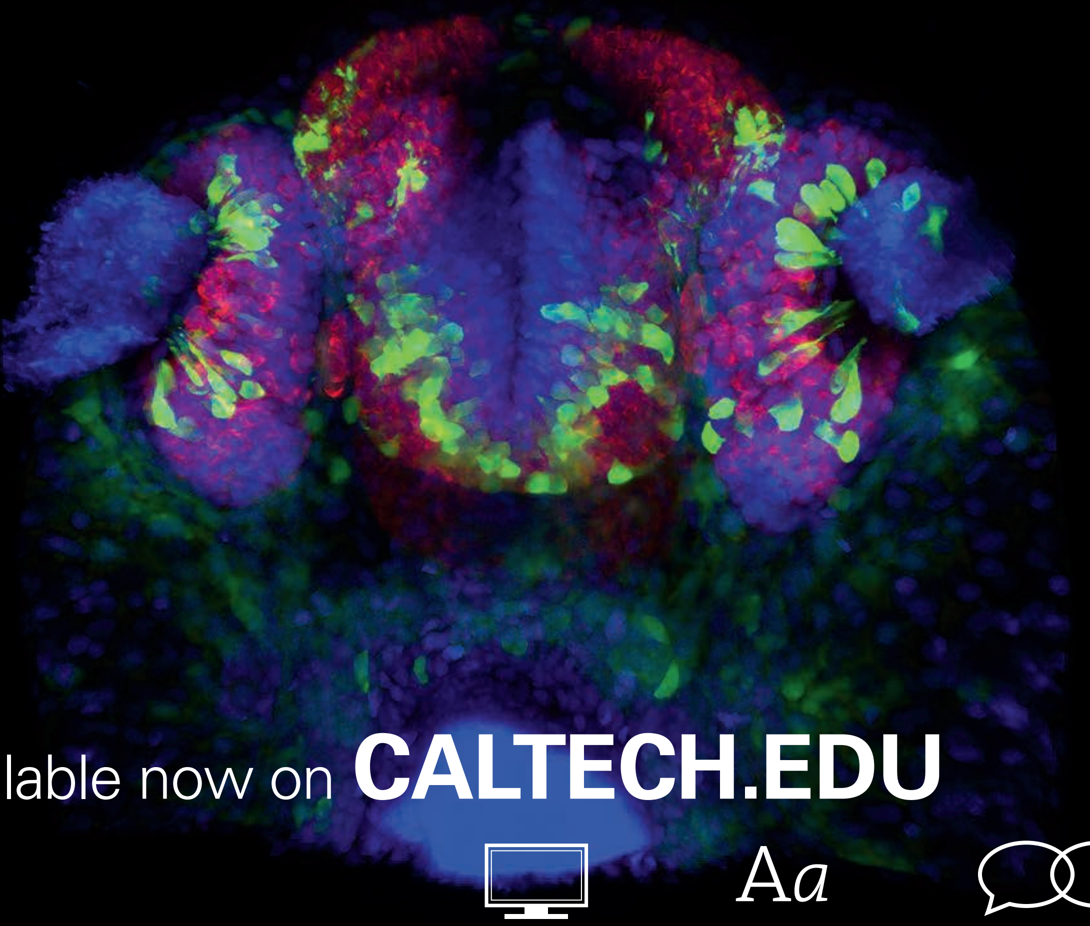
Although humans are the only primates who learn to speak and to comprehend speech, we would be in good company in the avian world: there, each of about 4,000 species of bird is able to pick up its own species' characteristic warbles. By investigating the neural basis of this example of motor learning in songbirds, UC San Francisco neuroscientist Allison Doupe and her lab members are deciphering the brain mechanisms that underlie vocal learning and what happens when those mechanisms break down.

During her TEDxCaltech talk, Mimi Kao—one of Doupe's postdoctoral fellows—described the team's research into the specialized areas of the bird brain known collectively (and fittingly) as the song system, and how this system allows a bird to replicate the complicated song it hears others of its species sing.

Even social motivation plays a role. When Doupe's team studied a juvenile male zebra finch in the process of learning his song, they found that, left on his own, he made the expected mistakes of a young'un—stopping part way through the song or stuttering through it. In the presence of a female bird, however, the suddenly motivated finch was able to reliably produce a good version of the song. "Like teenagers everywhere," Kao said, "this bird knew more than he was telling us." —*KF*



Eye Teaser *Caltech biologist Markus Meister's research focuses on image processing in the retina. At TEDxCaltech, his presentation featured the brain—or eye—teaser above. The tile with a dot on the left looks much darker than the tile on the right, but they are actually the same color. The illusion results from a process called lateral inhibition, which arises in the retina and elsewhere in the visual system. Here's how it works: the retina determines the relative darkness or lightness of an image by considering the local intensity at a particular spot minus the average intensity in the surrounding region. Thus, because bright tiles surround the dotted tile on the left, the retina reports on it as being dark when it sends info to the brain. Since dark tiles surround the dotted tile on the right, the retina "sees" and reports that tile as being relatively bright. Says Meister: "You can frequently identify the effects of image processing by considering simple experiments on perception, such as these kinds of visual illusions."*



available now on **CALTECH.EDU**

WHAT'S THAT SMELL?

Caltech biologists have found that neural-crest stem cells—the cells that give rise to such structures in the body as facial bones and smooth muscle—also play a key role in building the olfactory sensory neurons found in the nose. Learn more at **www.caltech.edu/news**.

Watch

Learn more about two decades of astronomical discoveries at the Keck Observatory from talks celebrating its 20th anniversary. Check out the videos at **www.youtube.com/caltech.**

Read

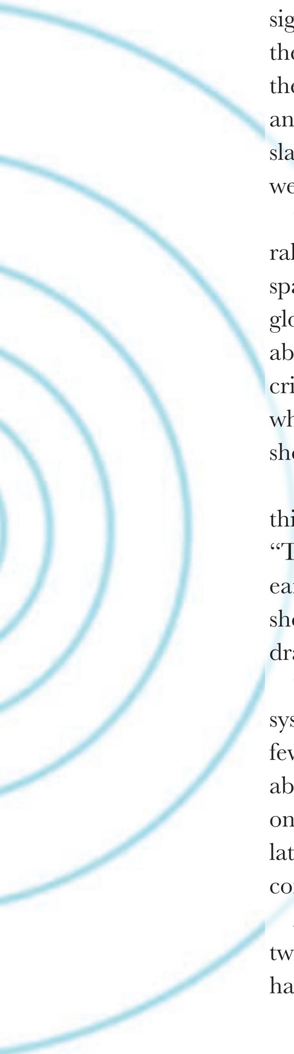
Experience Caltech through the stories of the extraordinary people who are behind our exploration, discovery, innovation, and impact. Click through the *2012 Annual Report* at **www.caltech.edu/annualreport2012.**

Engage

Enjoy music under the stars when MUSE/IQUE returns to the Caltech campus on Saturday, July 27, at 7:30 p.m. Find out more at **www.caltech.edu/calendar/public-events.**

Can We Predict

By Katie Neith



In April 2009, the Italian city of L'Aquila suffered a devastating magnitude 6.3 earthquake that toppled ancient buildings and left nearly 300 people dead. Dozens of significant aftershocks rocked the region, causing more damage and leaving tens of thousands of locals without homes. The main quake was preceded by a swarm of smaller temblors that caused general anxiety in the region. An official committee of scientists and emergency managers sought to calm this anxiety by saying that the swarm was a reassuring sign—pent-up energy was being relieved, thereby decreasing the chance of a larger earthquake. Two years later, even as the area was being rebuilt, six Italian earthquake scientists and a former government official were found guilty of manslaughter for their scientifically unjustified statement. They were sentenced to six years in jail.

The trial, which focused on the foreshocks and other natural phenomena that had occurred prior to the major quake, sparked outrage and debate among scientists around the globe. One question was whether earthquakes are predictable; another, whether scientists who advise the public are criminally culpable. Tom Heaton, a seismologist at Caltech who has dedicated his career to earthquake research, has a short response to the first question: no.

"Personally, I think you are only fooling yourself if you think you can predict an earthquake in detail," he says. "The reports of signs that seem to point to an oncoming earthquake are typically versions of what I call 'Texas sharp shooting.' Someone shoots the side of the barn and then draws the target *after* they shoot."

That said, Heaton does believe it's possible to build systems that can give people a warning mere seconds to a few minutes—max—before shaking from an earthquake is about to occur in a specific area. In fact, he's been working on such earthquake early warning (EEW) systems since the late 1970s, and he was the author of the first paper on the concept in a 1985 issue of the journal *Science*.

Although EEW research stood relatively still for nearly two decades after Heaton's seminal paper, the past 10 years have seen enthusiasm for EEW systems begin to grow.

"Things have really turned around," says Heaton. "The world just had to await the invention of Internet communication. In the '70s or '80s, we would have had to build our own rapid communication system. But now one of the key elements already exists."

Those advances have made it possible for fully functioning EEW systems to be built and implemented in Japan, Taiwan, Mexico, Turkey, and Romania in just one decade. And thanks to a recent $6 million award from the Gordon and Betty Moore Foundation, Caltech—along with UC Berkeley, the University of Washington, and the U.S. Geological Survey (USGS)—has been able to advance a West Coast EEW system.

"We're at the point where we are beta-testing a system that sends seismic-event information to us scientists and a few test users at the beginning of an earthquake," Heaton says. "It's currently being used to get other places—like emergency response agencies or power plants—accustomed to what they might do with the technology."

For instance, thanks to the system, Caltech seismologist Kate Hutton received a 40-second warning ahead of the waves from a 4.7 quake in Anza, California, on March 11 of this year. If this means what Heaton and others hope it does, that beta system—called ShakeAlert—might soon be the difference between preparedness and chaos.

GROWING ALERT

ShakeAlert utilizes a network of seismometers—instruments that measure ground motion—widely scattered across the western states. In California, that network of sensors is called the California Integrated Seismic Network (CISN) and is made up of computerized seismometers that send ground-motion data back to research centers like the Seismological Laboratory at Caltech.

"When an earthquake occurs, seismic waves radiate away from the source, like the waves on a pond after you've thrown a rock into the water," explains Maren Boese, a senior research fellow in the Seismo Lab. "Our computer algorithms can analyze these waves and can predict where

Earthquakes?

strong shaking will occur so quickly that an automated warning can be sent to more distant sites before the waves—and the shaking they cause—arrive. It's mainly a very fast information system."

Here's how the current ShakeAlert works: a user display opens in a pop-up window on a recipient's computer as soon as a significant earthquake occurs in California. The screen lists the quake's estimated location and magnitude based on the sensor data received to that point, along with an estimate of how much time will pass before the shaking reaches the user's location. The program also gives an approximation of how intense that shaking will be. Since ShakeAlert uses information from a seismic event in progress, people living near the epicenter do not get much—if any—warning, but those farther away could have seconds or even tens of seconds' notice, says Boese.

The hope is that an improved version of ShakeAlert will eventually give schools, utilities, industries, and the general public a heads-up in the event of a major temblor.

"You can use early warning to trigger a public alert and warn people to take protective steps, such as drop, cover, and hold on," Boese says. "But I think it's just as important to get psychologically ready for the shaking. Many people are really confused at the beginning of a quake and that's how they lose time. But if they already know that it *is* an earthquake—and they know that in a couple of seconds it will be over—that's really useful information that will reduce panic."

For many applications, like trains or elevators, actions will be initiated automatically after a warning is received. To be effective, the system must be reliable; you don't want to stop trains unless it really is a significant earthquake. On the other hand, the regions near the epicenter will have the strongest shaking and the shortest warning times, if any at all. Unfortunately, these are competing goals, Heaton says. While it may be feasible to get the first messages out very quickly, those messages will be based on minimal data and will not be as reliable. In order to determine the best trade-off between speed and reliability, James Beck, an engineer at Caltech, is working to design a type of cost-benefit analysis that can be applied to automated decision-making processes.

Above: Maren Boese and Jim Beck

Above right: Tom Heaton

"When you're dealing with earthquakes, there is enormous uncertainty," he says, "and only a few seconds in which to make a decision. So we quickly realized that we have to take humans out of the loop and somehow capture the essence of human decision making in a computer."

To do this, Beck and his lab are developing a probability-based automated decision-making earthquake application called ePAD. Its focus is on making fast and reliable decisions about whether the system should initiate a mitigation action—such as slowing a train or halting surgery—or not.

"One of the biggest challenges is that all earthquakes, in some sense, start out nearly the same," says Beck, who envisions that ePAD, when ready, will one day be incorporated into the ShakeAlert system. "A large earthquake is big simply because it ruptures a fault over a longer distance—there's not much else about it at its onset that signals that it's different from a smaller quake. When you're trying to determine whether it's worth sending out a warning, there is a real trade-off: you want the system to be quick in sending an appropriate response, but you also want it to be reliable, only raising an alarm when it's absolutely needed. It's very hard to get both."

The task of improving the speed and dependability of the ShakeAlert system is something that Boese and Heaton are undertaking as well.

"Some people think it's just a trivial problem of knowing that it's a certain sized earthquake and figuring out when the waves will get to you and that's it," says Heaton. "There is far more to making intelligent decisions than just that simple level of information."

FIGURING OUT FINDER

Making use of more complex data, Heaton—along with Boese and Egill Hauksson, a senior research associate in the Seismo Lab—has developed an algorithm called a Finite Fault Rupture Detector (FinDer), which can deconstruct an earthquake rupture in real time and provide additional data to the ShakeAlert system.

Although a rupture begins at a point, it can spread over tens of kilometers in a larger earthquake. FinDer works by looking for stations with intense, high-frequency shaking that is typically seen only very close to a rupture. The algorithm then compares the spatial pattern of near-source stations with patterns determined from a suite of already-understood large-earthquake scenarios. This provides more detailed information about which direction the quake might be heading and how quickly.

"I think it's really a big step forward," Boese says. "With FinDer, you can really keep track of the rupture as it is evolving."

The FinDer group is taking its ideas one step further by tapping into a huge database of 3-D simulations of seismic waves that will provide information about how seismic waves act based on location—leading, the team hopes, to better ground-motion predictions. For example, there is a deep basin below Los Angeles in which seismic waves seem to become trapped, reverberating for long periods during a rupture and making the shaking stronger. But, simulations show, bedrock yields less shaking. Incorporating this information into ShakeAlert, then, would mean that people living on bedrock would receive a different level of alert than those on softer soil.

"Once you know there is a major earthquake, the system should be able to immediately tell you how strong the shaking will be at your particular site," Boese says. "This database of simulations already exists, so it's nothing new, but now we're applying it to EEW."

Still, while significant strides have been made to improve the current EEW prototype, many challenges remain before scientists will be able to bring a statewide, public-access system to fruition.

Beck feels that one of the biggest technological challenges is to make the software more discriminating when it comes to detected events that aren't really California earthquakes—such as sensor malfunctions or local man-made ground shocks—or small earthquakes that are perceived as large earthquakes because they are part of a complex sequence of quakes that produce overlapping signals.

Boese expects that educating the public about EEW systems will be an additional hurdle. "People need to know what early warning is, its benefits, and—most importantly—its limitations," she says. "We need to be able to explain that it's only an additional tool they can use to get information; it does not replace seismic retrofitting or other precautions."

One of the final—and possibly highest—hurdles will be finding someone to operate a statewide EEW system. The obvious candidate would be the USGS—but because its budget, which comes from the federal government, has steadily decreased over the past 30 years, it would require a lot more resources in order to take on this expanded role. In April, the federal government did pledge $5 million to improve the EEW system in Southern California, but the USGS says that this is just a fraction of what will be needed to implement a statewide system.

"It's possible that the right politicians could make that happen, and certainly an adequate seismic tragedy could make that happen," says Heaton. "Unfortunately, the reality of our business is that seismic tragedies are often among the most important instigators of new developments. I guess it's a little like war in that respect."

Nonetheless, the researchers agree that the benefits of putting an EEW system in place are worth the tackling of its technological and political challenges.

"As a scientist, it's very exciting that our research is now allowing us to make a prediction and then test it within seconds," Heaton says. "Usually, in our business, we do a study that includes a guess about something that could happen in the future, and *maybe* in your lifetime you could test it, but probably not. Early warning is different. And that's extremely satisfying."

All three researchers also agree that, on a broad societal scale, an EEW system could give the public a few seconds to take actions that might greatly reduce losses in the case of a severe earthquake, including the much-discussed Big One.

"Earthquakes will still occur, and there will be damage," says Boese. "But we hope that, with an early warning, we can protect property, shorten recovery times, and, most importantly, save lives." e&s

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James Beck is the George W. Housner Professor of Engineering and Applied Science.

Maren Boese is a senior research fellow in geophysics at Caltech's Seismological Laboratory.

Thomas Heaton is director of the Earthquake Engineering Research Laboratory at Caltech, and a professor of engineering seismology.

Research on EEW systems at Caltech is funded by the Gordon and Betty Moore Foundation and the U.S. Geological Survey.

WHAT CAN WE DO ABO

By Dave Zobel

Here's a not-news flash: Earth's polar ice caps are melting.

The melting is largely due to a rise in the global mean temperature. Which is largely due to an increase in atmospheric greenhouse gases. Which is largely due to human activity. It's a domino chain, set tumbling by *Homo sapiens*, and the next time some dogmatist tries to tell you otherwise, you can say that Paul Wennberg told you so.

Wennberg, the R. Stanton Avery Professor of Atmospheric Chemistry and Environmental Science and Engineering at Caltech, is the acting director of the Ronald and Maxine Linde Center for Global Environmental Science, a consortium of close to 30 Caltech research labs that are attacking climate change from as many different angles. (The old saw that everybody talks about the weather but nobody does anything about it, observes benefactor Ronald Linde gleefully, is evidently no longer true.) The center's goal: to develop a quantitatively rigorous understanding of the mechanisms that determine Earth's climate—both past and future—and how that climate in turn influences the biosphere.

Why are so many investigators needed? Because, as Wennberg grimly acknowledges, the underlying problem is still poorly understood. "We have only a poor description of how clouds form and persist," he says, "and this ignorance limits our ability to predict the future climate. While we know that warming in the polar regions will reduce the extent of glaciation, the rate at which the ice melts—and the sea level increases—is highly uncertain. Perhaps least understood is how Earth's biosphere, both on land and in the ocean, will respond to changes in climate and CO_2."

Given such a chaotic landscape, no single piece of the puzzle solves the whole; no magic bullet offers a quick fix; no scientific discipline alone—and certainly no solitary researcher—holds the key. Instead, Caltech's chemists and physicists must work alongside its engineers and environmental scientists, its isotopic biogeochemists and molecular geomicrobiologists.

Mapping climate change's ubiquitous tendrils, Wennberg says, will require these scientists to make the most of the interdisciplinary tools and approaches available to them.

LOOK—UP IN THE SKY

Of all the footprints humans have left on the biosphere, perhaps the muddiest belong to the greenhouse gases. These include, in addition to media darlings carbon dioxide and methane, such culprits as carbon monoxide, nitrous oxide (no laughing matter in this context), and water vapor. The global warming they cause is real and measurable and can have wide-ranging effects on the environment.

UT CLIMATE CHANGE?

For example, we have ancient plants to thank for making our world habitable by producing much of the oxygen in our atmosphere. It's painfully ironic that, today, the descendants of those plants are experiencing climate change caused by atmospheric changes resulting from the burning of fossil fuels—the remains of those same ancient plants.

In hopes of gaining a better understanding of what exactly we're standing under, many Caltech researchers are studying the skies. Wennberg, for instance, has created and deployed the worldwide Total Carbon Column Observing Network (TCCON), which detects the fingerprints of various atmospheric components by measuring the spectroscopic bite they take out of the sun's incoming rays. One of TCCON's earliest successes was the discovery of more methane over Los Angeles than current models could account for. Can it be traced back to some local source of pollution, or is its origin more global? To find out, Wennberg is considering recruiting students to drive around the L.A. basin with methane-monitoring devices.

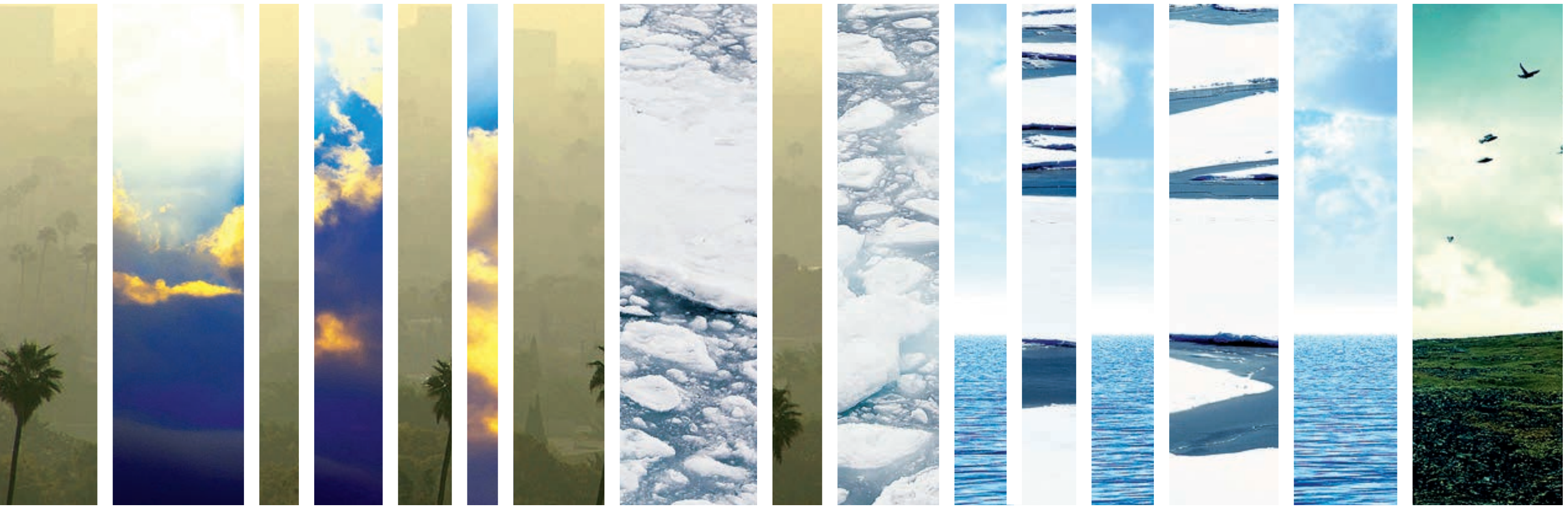
Climate change, incidentally, produces many effects, of which global warming is just one. For example, work done by environmental scientist Richard Flagan, the Irma and Ross McCollum–William H. Corcoran Professor of Chemical Engineering, points to climate change as the key to understanding a longstanding medical conundrum: How can pollen particles, which are too large to get past the nasal cavity, trigger asthma deep in the lungs? His studies have shown that when local wet/dry cycles are disrupted, pollen grains rupture on the plant—and the resulting bioactive microfragments are small enough to invade the lungs and wreak all manner of respiratory havoc.

In fact, the atmosphere is a complex, multilayered chemical laboratory. Even the stratospheric trace gases (found kilometers above us and as hardly more than faint wisps on a spectrograph) can exert their photochemical influence on the biosphere—i.e., us. This, says chemical physicist Mitchio Okumura, is an effect we cannot ignore.

THE MAIN CHALLENGE(S)

Actually, it's unfair to blame global warming solely on the greenhouse gases. The global heat engine, a system characterized by a continual flow of heat toward the poles, is regulated by a complex interplay of activities all over Earth's surface: on the sea and on the land as well as above and below them. One such activity is the movement of air and water, both in obvious local patterns and in larger, more stately dances that nonscientists rarely notice.

"People are often surprised to learn that there's something called the North American monsoon," remarks environmental scientist Simona Bordoni. "But it's a very real phenomenon, responsible



for summer thunderstorms and flash floods across the deserts of the Southwest and Mexico." Bordoni studies the interactions between mid- and large-scale atmospheric circulations. Using satellite observations of ocean-wave roughness to estimate surface wind velocity, she's traced broad changes in the monsoon's northernmost extent back to wind surges over the relatively narrow Gulf of California—a real-world butterfly effect.

Nothing evolves in isolation, particularly under the stresses produced by a constantly shifting climate.

Those butterfly wings may well be messing with the Greenland ice sheet as well. When warm winds—warmer than they should be, at least—cross the sheet's surface, they give rise to impromptu lakes of meltwater, which then drain away through cracks in the ice. Victor Tsai, who studies solid-earth geophysics, says that if this runoff reaches the underlying ground without refreezing, its lubricating effect might very well hasten the ice sheet's glacial march toward the shore. The result would be an increase in the iceberg calving rate, which, like adding ice cubes to a drink, could lower the average temperature of the Greenland Sea, kicking off yet another set of potential consequences.

While such a model is easy to visualize, Tsai cautions that at this point it's still only hypothetical. "The interactions between atmospheric warming, the ice sheet, and the ocean are intricate," he notes, "and that makes it challenging to understand the whole system."

Those sorts of interactions are similarly challenging for Andrew Thompson, a specialist in physical oceanography who is focusing on modeling the effect of climate perturbations on the circulation of ocean currents—a process that's actually far less straightforward than those looping arrow diagrams you remember from earth-science class. Consider the Antarctic Circumpolar Current, flowing perpetually eastward around Antarctica along a swath of latitude never interrupted by land. That fluke of geography sets up a fierce system of ocean jets that encircle the South Pole like a liquid skirt. These jets act as a gateway that controls the invasion of warmer water from equatorial latitudes as well as the escape across the ocean's abyssal plains of icy waters formed under ice sheets. This cold Antarctic Bottom Water is the densest seawater on the planet, and it influences everything from the amount of carbon dioxide in the atmosphere to the distribution of tiny krill, a keystone of the global food chain. The slightest imbalance in the system could have a ripple effect that substantially alters Earth's climate.

To model the oceanic effects of climate perturbations, Thompson sends autonomous robotic systems diving and drifting through the Southern Ocean, where they track their own positions via GPS and report local current data via satellite. "Using CITerra [a Caltech supercomputer cluster], we can compare these field observations with simulations of ocean circulations," he explains. "The results tell us how small-scale ocean flows govern ocean-ice interactions and feedback on sea level and other global aspects of climate."

Given such a sensitive global system, how can humankind hope to tweak the thermostat even the tiniest bit without triggering a catastrophe? Presumably, the first step is to identify the main stumbling blocks, of which each researcher seems to have a particular "favorite." For atmospheric scientist John Seinfeld, the John E. Nohl Professor and professor of chemical engineer-

ing, it's our limited understanding of two specific interrelated factors: the life cycles of aerosols, and the microphysics of clouds themselves. "Aerosols reside in the air for only a week or two, but that difference has a large effect on their climatic influence," he says. "That's because clouds form on these particles. Since the Industrial Revolution, the global level of aerosols has increased, and yet determining just how this increasing burden of particles has affected the world's clouds—and then how those clouds affect climate—remains one of the grand challenges in climate science."

Planetary scientist Andrew Ingersoll, on the other hand, is most focused on teasing apart the net-energy equation. "Of all the planets in the solar system with atmospheres, Earth absorbs the most energy per unit area, and yet it has the weakest winds," he says. That doesn't quite make sense, he adds, since air movement tends to be linked to and driven by differences in heat between ground and air. What's slowing down our winds? Nobody knows. "Clearly," Ingersoll says, "there's a lot we still don't understand about climate."

CLUES ALL AROUND US

One way to try to get a better idea of what is going on is to look to the past. Climate change is, it turns out, hardly an invention of modern humanity. Cores extracted from ancient corals and stalagmites by geochemists John Eiler and Jess Adkins reveal dramatic shifts and upheavals in the paleoclimate. Indeed, geobiologist Woody Fischer has found evidence in sedimentary rocks that correlates several mass extinctions—not just that of the dinosaurs—to climate-change events. And there's evidence that it was climatic pressure that drove ancient bacteria to evolve photosynthesis; by studying the chemical footprints they left behind, molecular geomicrobiologist Dianne Newman can trace the various branching pathways they took.

This suggests that an improved understanding of the complex interdependence between Earth and its inhabitants is vital. "We've known since Darwin that the evolution of species is shaped by the physical environment," explains biogeochemist Alex Sessions. "But it turns out that the relationship is reciprocal: under the influence of biology, the planet itself is evolving." An example: after a wildfire scours a grassy hillside, the resulting erosion deposits sediment downstream; as plants take root in the newly created wetlands, the soil's angle of repose increases, and new hills arise.

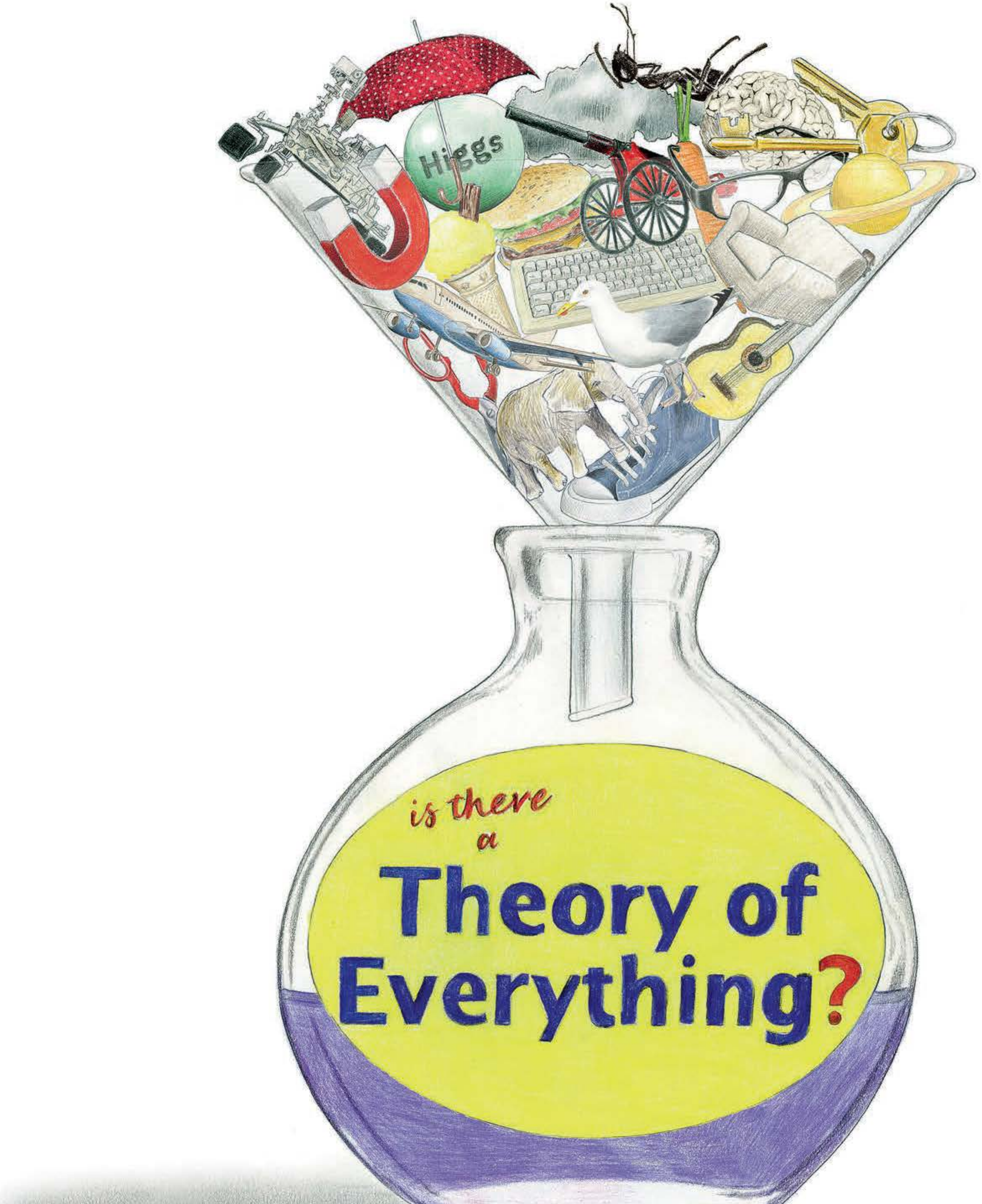
Nothing evolves in isolation, of course, particularly under the stresses produced by a constantly shifting climate. In this regard, it appears that one of the humblest organisms on the planet has much to teach the most advanced. Environmental microbiologist Jared Leadbetter has found that the termite would be unable to process lignocellulose—the substance that makes up the cell walls in wood—if its gut didn't harbor a digestive assembly line powered by a pair of cooperating bacterial species. Geobiologist Victoria Orphan is analyzing two cohabitating deep-sea microorganisms that work together in a chemical chain reaction for producing and consuming methane.

In both these cases, each microbial species holds the key to just one part of the process. Only through symbiotic cooperation are they able to pull their energy-transfer rabbit out of a hat.

And *that* makes a fitting analogy for the current state of climate-change research: where convergence is the watchword, where a new wave of portmanteau specializations has blurred the boundaries between scientific disciplines, and where Caltech's researchers, armed with a dazzling array of techniques and toolkits for bringing worldwide change to a changing world, are poised to uncover the answer to climate change.

Once they've worked out the question, that is. E&S

The climate-change research discussed in this article is funded by a number of sources, including the Department of Energy and the National Science Foundation.


Higgs
is there a
Theory of Everything?

By Marcus Y Woo

It's beautiful, even elegant, in its simplicity. It's profound, encapsulating all of nature in a few mathematical symbols and relationships pithy enough to fit on a T-shirt. It's the so-called theory of everything, a complete understanding of the laws that govern the entire universe—and it's a dream that physicists have been pursuing for centuries.

One of the first attempts at a basic theory of nature was made in Greece in the fifth century BC, when Democritus proposed that everything was made of atoms. Science has since not only proven the existence of atoms, but has shown that atoms themselves are composed of even smaller, more fundamental particles such as electrons and quarks. But despite breakthroughs over the last century, physicists have yet to develop a single, unifying framework that explains all natural phenomena at their most basic level. Even Albert Einstein spent the final chapter of his life hunting—in vain—for such a theory.

And, if so, what is it?

Admittedly, the theory of everything is a bit of a gimmick. After all, no theory can explain *everything*. Such a theory, if and when physicists find it, won't explain why unemployment is high, why people fall in love, why life exists on Earth, or whether it will rain tomorrow. "You're never going to explain everything from just the basic laws of physics—it's crazy," says Caltech physicist John Schwarz, who for more than 40 years has been on his own quest for a unified theory. "When people use that phrase—theory of everything—what do they mean by 'everything'? That can cause a lot of confusion."

So what exactly is it? The theory of everything—or, as some physicists prefer to call it, a unified theory—refers to a single, cohesive framework that explains how and why all the fundamental particles and forces in the universe behave and interact as they do. That may sound esoteric, but you can indeed argue that such a theory is the basis for, well, everything. From carrots to brains, from planets to stars, everything is made of elementary particles, and the properties of everything ultimately depend on how those particles interact with one another.

TOWARD UNIFICATION

There are four fundamental forces of nature: gravity, the electromagnetic force, the strong force (which holds atomic nuclei together), and the weak force (which is responsible for the nuclear reactions that keep the sun shining and for radioactive decay, which generates the energy that drives geological processes on Earth). Those forces govern the behavior of a smorgasbord of elementary particles, including electrons, neutrinos, quarks, and the Higgs boson, the probable discovery of which physicists announced amid much fanfare last summer at the Large Hadron Collider (LHC) in Geneva.

Those particles, along with the electromagnetic, strong, and weak forces, are described by the so-called standard model, a theory that's been confirmed again and again by experiments, making it one of the triumphs of 20th-century physics. Many Caltech physicists—including Nobel laureates Richard Feynman, Murray Gell-Mann, and David Politzer—helped lay its foundations. But, as many physicists today are eager to note, it's incomplete.

“The standard model is great,” says Caltech theoretical physicist Hirosi Ooguri. “It explains almost everything we know about the physics of elementary particles. But that’s only 5 percent of our universe.” The other 95 percent? Dark matter and dark energy. Dark matter is the unseen stuff that makes up 27 percent of the cosmos. Dark energy is an entirely different beast, a force that accelerates the expansion of the universe and accounts for about 68 percent.

> **“It wasn’t a problem that I had set out to solve, but it kind of hit me over the head.”**

And then there’s gravity.

“From the theorist’s perspective, the most pressing issue is that the standard model of particle physics does not contain gravity,” Ooguri says.

Indeed, gravity is a bit of an oddball. Although it seems such a tangible and ubiquitous force in our daily lives, it’s extremely weak compared to the other forces. After all, a small magnet can lift a paperclip off a table using the electromagnetic force, thus overpowering Earth’s gravity.

Einstein’s theory of general relativity is a theory of gravity, describing the force as a warping of space and time—the fabric of the universe—caused by anything with energy or mass (which are equivalent, according to $E = mc^2$). General relativity has been proven accurate time and time again, from explaining a peculiar shift in Mercury’s orbit to helping your GPS pinpoint your location. Still, it’s limited.

One problem is that general relativity does not get along with the bizarre, probabilistic laws of quantum mechanics, which is the backbone not only of the standard model but of all physics—especially at small scales. In order to probe things like the centers of black holes or the moments after the Big Bang, physicists need to fuse quantum mechanics with gravity. But when they try, they get nonsensical descriptions of nature that involve infinite numbers. “There’s no evidence that quantum mechanics is wrong,” notes Caltech physicist Mark Wise. “It seems to be the foundational concept for physics—and gravity should fit into that.” But right now it doesn’t.

The unifying theory that physicists long for is therefore a quantum theory of gravity, one that unifies quantum mechanics with gravity and that also includes everything the standard model explains—plus dark matter and dark energy. But does such a theory even exist?

“I’m convinced there *is* a theory,” Schwarz says. After all, there must be *some* explanation for what we don’t yet understand. Whether physicists will ever come up with such a unified theory, however, is uncertain. Over the decades, they’ve proposed various candidates. So far, the most successful among them—though not yet fully formulated—is string theory.

ALL STRUNG UP

As its name suggests, string theory—sometimes known as superstring theory—posits that the universe isn’t made of fundamental particles, but rather of stringlike objects that weave through reality like thread in the fabric of space and time. These strings vibrate, and the modes in which they vibrate manifest themselves as electrons, neutrinos, quarks, and other fundamental particles—much as the vibrations of guitar strings manifest themselves in a variety of musical notes. In string theory, the properties of different types of string—their tension, for example—give rise to the characteristics of their particular particles, such as mass, spin, and electric charge.

String theory was originally developed in the 1960s as a way to explain how the strong force works. It couldn’t, as it turned out. And so, within a few years, physicists had tossed it aside in favor of a more successful theory called quantum chromodynamics—contributions to which in the ’70s would win Politzer his Nobel in 2004.

Then, in 1974, Schwarz, who had joined Caltech two years previously as a research associate, and Joel Scherk, a visiting scientist at Caltech at the time, realized that string theory predicted the existence of a strange new particle whose properties precisely fit those of a hypothetical particle called the graviton.

To understand why this is significant, you need to know that, in the standard model, every fundamental force is mediated by a particle. The electromagnetic force, for example, is carried by photons. (A photon is a particle of light, which, by way of quantum weirdness, can also be thought of as a wave made up of electric and magnetic fields.) And so, if there is to be a quantum theory of gravity, it too will need a particle to carry it: the still-undiscovered graviton. String theory, which had been an esoteric idea destined for the scrap heap of physics, became reimagined as a possible quantum theory of gravity once Schwarz and Scherk realized it incorporated the graviton.

The discovery, Schwarz says, was at once startling and mathematically beautiful. "What kept me going was the realization that it could make gravity consistent with quantum mechanics," he recalls. "It wasn't a problem that I had set out to solve, but it kind of hit me over the head, and I thought, 'Hey, that's pretty good—I'd better follow that up.'"

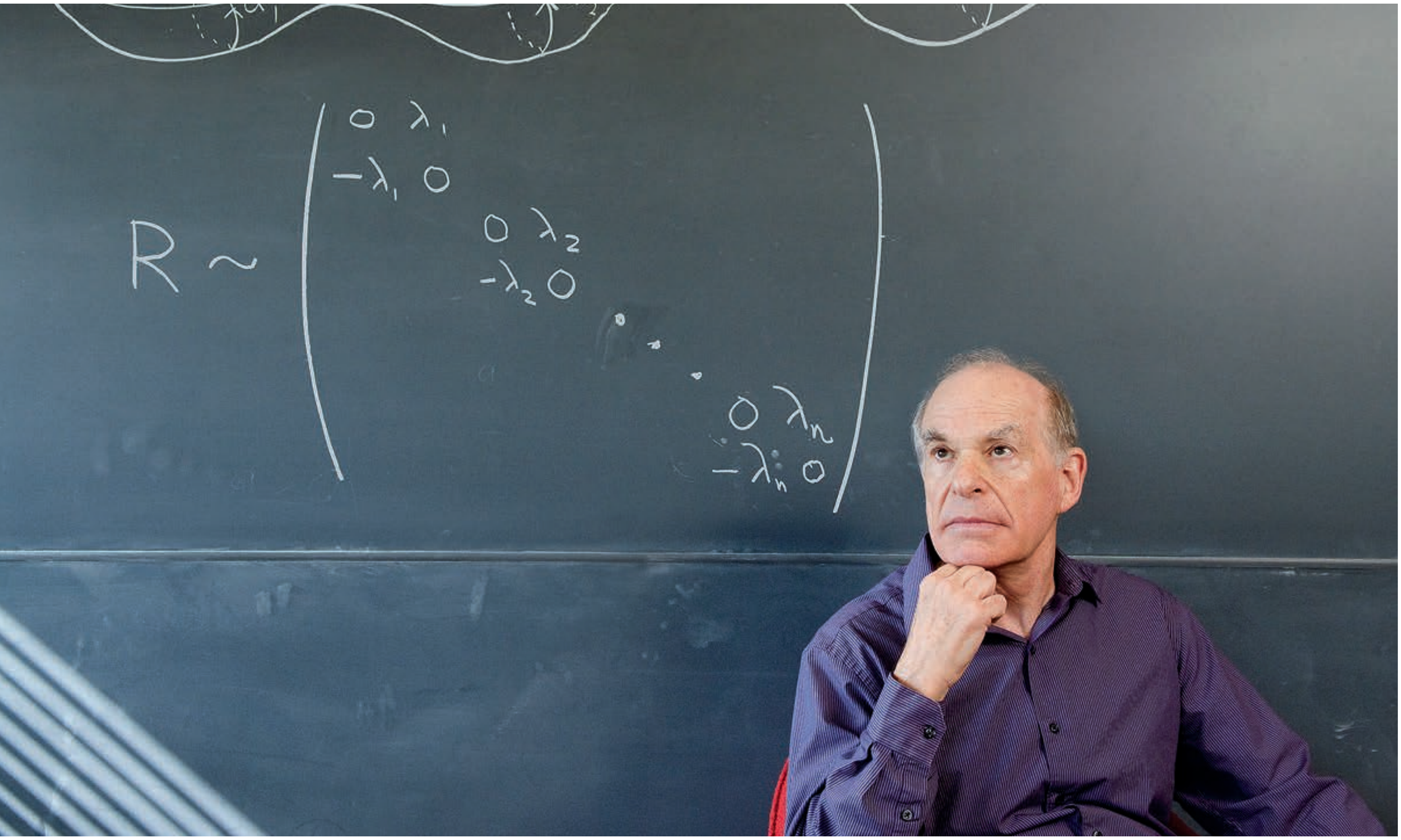
When Schwarz and Scherk published their results in 1974, no one seemed to pay attention. That didn't deter Schwarz, who, convinced that the mathematical beauty of string theory wasn't happenstance, pressed forward. He began working with Michael Green—now at Cambridge University in England—to fix some of the mathematical inconsistencies in string theory that prevented it from fully explaining all of the physics in the standard model. Ooguri credits Caltech and, in particular, Murray Gell-Mann for supporting Schwarz in his lonesome—and rather risky—quest. When Schwarz and Green eventually succeeded, in 1984, string theory became a bona fide candidate for the title of unified theory. And this time, physicists the world over took notice.

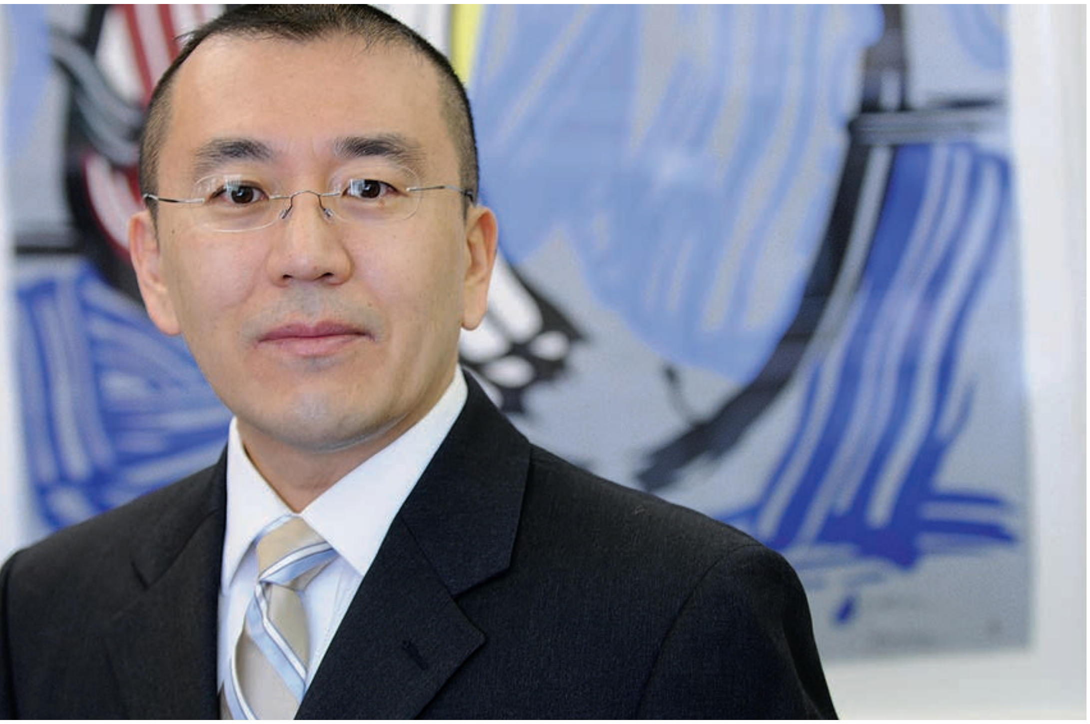
Among them was Ooguri, who had just started graduate school in Japan. "I heard a rumor that there was some great discovery made in the United States at Caltech," he says. Looking into it further, he realized that it provided a base from which the properties of all elementary particles could be derived—something that the standard model, a rather ad hoc theory, does not do. When Ooguri realized that string theory provided these so-called first principles, he was amazed. "I thought it was beautiful," he says.

SEARCHING FOR STRINGS

Beautiful, but mathematically and conceptually complicated. And that, at least in part, is due to one of the hallmarks of string theory: it requires (at least) *nine* dimensions of space.

Below: Caltech physicist John Schwarz is one of the founders of string theory.





Above: Hirosi Ooguri is one of Caltech's leading string theorists.

That's six more than the three we're all acquainted with: up/down, left/right, and forward/backward. How could there be another six that we can't see or experience? String theory says those extra dimensions are so curled up and thus so small we don't even notice them. To get an idea of what that means, imagine a box that's placed far away from you. Although you know the box is three-dimensional—with length, width, and depth—from where you're standing it appears so small that it looks like a point, with no dimensions at all. Analogously, these extra dimensions would be too tiny for us to experience them.

Trying to imagine six curled-up extra dimensions gives most people a headache; now imagine the math needed to describe them. One major hurdle was in computing the distance between two points in six dimensions—a basic task without which you can't calculate much in a theory that requires so many dimensions. "I took that as a challenge," says Ooguri, who spent the 10 years after Schwarz and Green's breakthrough tackling it. Although today's physicists and mathematicians still don't know how to compute distances in the higher number of dimensions used in string theory, Ooguri and other scientists successfully developed mathematical tools that can be used to circumvent the problem and make physical sense of the math.

As physicists continue to delve deeper into string theory, developing more mathematical tools and ideas, the field has progressed rapidly. But there remains a major problem: there is no experimental or observational evidence to support string theory, other than the existence of gravity itself.

Which is not to say no one has tried. Indeed, much of the current scientific effort around string theory is focused on figuring out ways to test it. One possibility would be to observe strings that originated in the early universe. The strings by now would be so stretched by the universe's expansion that they should span the entire cosmos. They'd be extremely thin, sure, but they'd also be dense enough to create noticeable ripples in space and time, bend light, or produce other effects detectable by astronomers. And yet, so far, no one has been able to observe them.

Another way to find evidence for strings is to probe nature at its deepest and most fundamental levels—to access phenomena at increasingly tiny scales. And to reach those extreme scales, you need to slam particles together with extreme energies.

Which is why so many physicists—including those hoping to find hints of string theory—flock to the LHC, the most powerful particle accelerator in the world. By colliding particles at near-light speeds, physicists at the LHC can create matter that's as hot and dense as the universe was immediately after the Big Bang. The hope is that those collisions will reveal signs of extra dimensions—or that they will provide evidence to bolster an idea called supersymmetry, which Schwarz helped originate as an essential feature of string theory.

All particles can be categorized as either bosons or fermions, and supersymmetry is a type of symmetry that relates the two. All of the normal matter in the universe is composed of fermions (such as electrons and quarks); the force-carrying particles are bosons (such as photons and gluons). Every particle has a hypothetical "superpartner" that's of the opposite type; for example, an electron's superpartner is a boson called a "selectron." None of these superpartners have been discovered, however, and they're thought to be extremely massive and unstable—disappearing almost as soon as they're created. The only way to see if they exist is to be watching when they're created—and the only way to create them is by smashing other particles together at places like the LHC.

"If there were any experimental evidence of that sort, it would be extremely exciting," Schwarz says.

Unfortunately, no one has seen anything like an extra dimension or evidence of supersymmetry at the LHC yet, although physicists—including a Caltech team led by Harvey Newman and Maria Spiropulu—are still on the hunt. Schwarz and his colleagues aren't worried: it's still early, physicists say, and the LHC is now in the middle of an upgrade that will double its energy for its next experimental run, planned for December 2014. There's a fair chance that at those higher energies, the LHC will be able to detect supersymmetric particles, Schwarz says, and that would be highly encouraging for string theory.

The chances the LHC will be able to find extra dimensions, however, are a lot smaller. That's because, as Schwarz explains, the amount of energy likely needed to find evidence for extra dimensions may be beyond the reach of the LHC—even the souped-up version.

That's not too surprising since, if you compute the energy at which phenomena predicted by a unified theory would definitely occur, the answer you get is a number that's a *thousand trillion* times higher than what's possible at the LHC. "That's where you're going to find the characteristic phenomena of any relativistic quantum theory of gravity—whether it's string theory or any competing idea," Schwarz notes. "But such phenomena are inaccessible."

THE QUEST CONTINUES

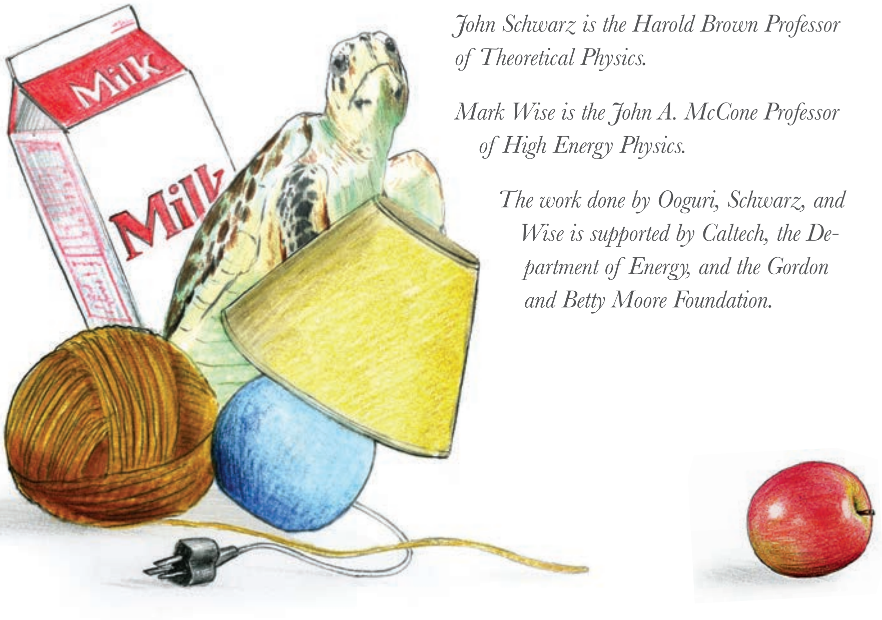
If there's no experimental evidence for string theory—and if any potential evidence is more or less out of reach—then why are so many physicists still clinging to it? For one thing, there just aren't many good replacement theories. But more importantly, physicists say, recent mathematical developments in this area are just too compelling to ignore, as theorists uncover relationships that connect and unify seemingly disparate mathematical objects, structures, and concepts that are part of string theory.

"The bottom line is, people who work on string theory have developed a sense that they're dealing with a mathematical structure that has some extraordinarily deep features that are absolutely fascinating," Schwarz says.

Plus, string theory seems to have everything that's needed for a unified theory. "Because it consists of just one structure—a string—and it has the basic ingredients to describe everything we know about nature, we're optimistic that somewhere in this framework the theory can make contact with the real world," Schwarz says.

"If string theory were not promising, and if we were not making progress, talented people wouldn't come to this area and push this forward," Ooguri adds. And they are definitely coming. In the early days, Caltech's string theory group—which was one of the most active in the world—consisted of Schwarz and maybe a couple of visitors or students. Today, Caltech's group includes about a dozen graduate students and postdocs. In addition to Schwarz and Ooguri, theoretical physicists Anton Kapustin and Sergei Gukov also do research relating to string theory.

Of course, even if string theorists are on the right track, they may still be decades from unveiling a full-fledged unified theory. After all, they have to invent entirely new branches of mathematics to describe their theory. "We want to identify the fundamental laws that—in principle—mathematically explain everything," Ooguri says. "That's a very ambitious undertaking. It's not something you can hope to achieve in just a decade or two."



Even if string theory fails to be crowned as *the* unified theory, many feel its mathematical spin-offs alone will have made it worthwhile. In the last few years, for example, physicists have used mathematical tools that were developed for string theory to describe the strange quantum states of new kinds of materials such as high-temperature superconductors.

And so, despite its challenges, physicists press on toward a theory of everything with hope and optimism. The scientific method demands diligent exploration, after all, and to a scientist such a quest is never futile.

"It's never pointless when you're trying to figure out what the laws of nature are—even if it ends up that they're not found in the direction you were pursuing," Mark Wise says. "I mean, that's what physics is about. It's high risk, high reward. And we certainly want to take the risk." e&s

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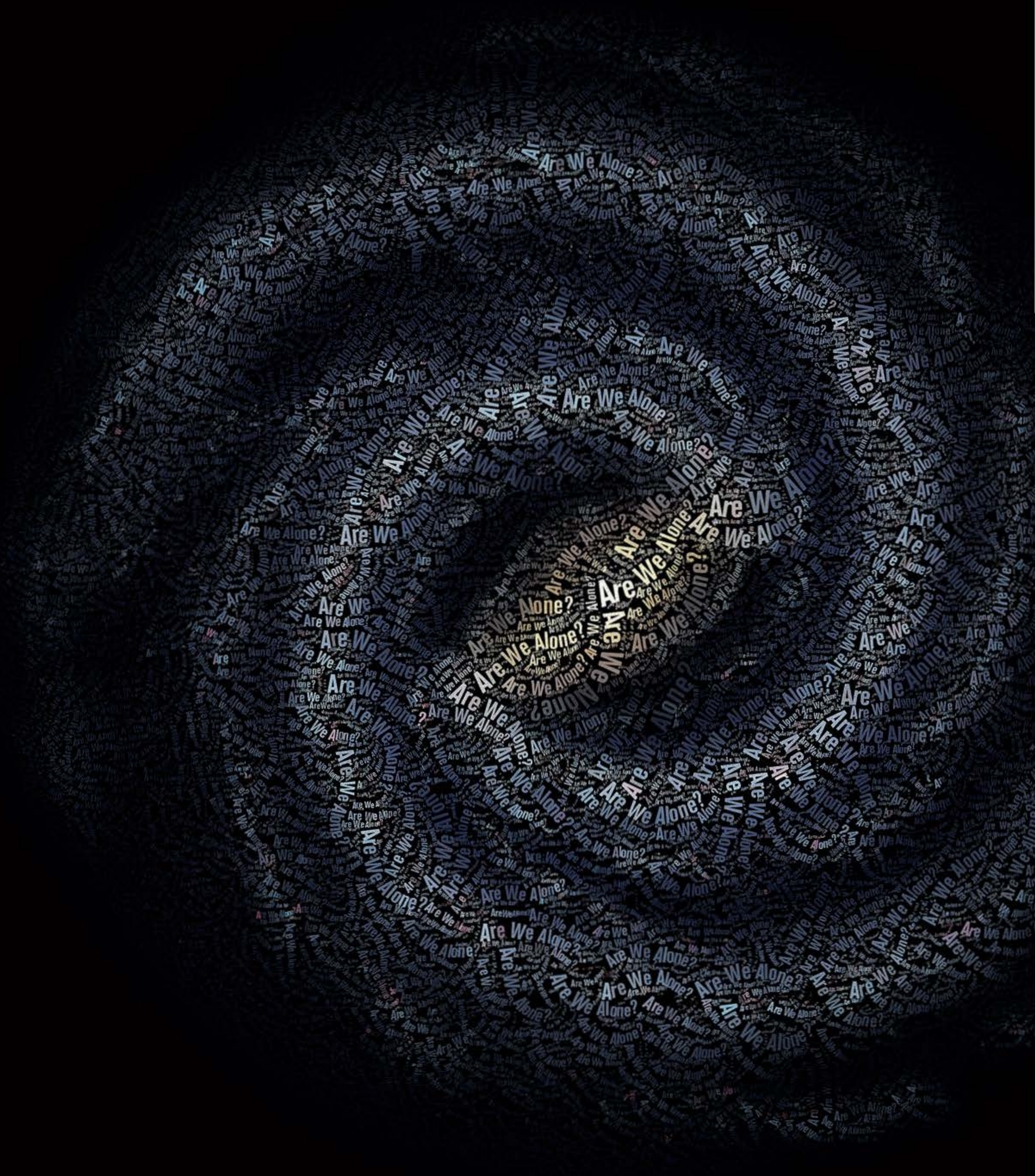
Hirosi Ooguri is the Fred Kavli Professor of Theoretical Physics and Mathematics. His work is supported by a Simons Investigator Award.

John Schwarz is the Harold Brown Professor of Theoretical Physics.

Mark Wise is the John A. McCone Professor of High Energy Physics.

The work done by Ooguri, Schwarz, and Wise is supported by Caltech, the Department of Energy, and the Gordon and Betty Moore Foundation.



Are We Alone?

Are We Alone?

By Kimm Fesenmaier

Thirty years ago—not even the blink of a cosmic eye—we had no real proof that planets existed beyond our solar system. Certainly, there was the hope that such extrasolar planets, more commonly known as exoplanets, were out there, and there was scientific support for the belief that we would find them. Still, until 1991, when astronomers first detected exoplanets orbiting a pulsar—the dense remains of a dead star—we and our seven solar system counterparts were essentially alone. Four years later another team found an exoplanet, dubbed 51 Pegasi b, orbiting a more sunlike star.

Fast-forward to today—an era in which it's actually difficult to keep up with the discoveries of and about exoplanets. At this point, the number of exoplanets that have not only been seen but confirmed as planets by follow-up observations and analyses has skyrocketed to more than 800, with an additional 2,000-plus unconfirmed candidates waiting for their chance to be officially recognized.

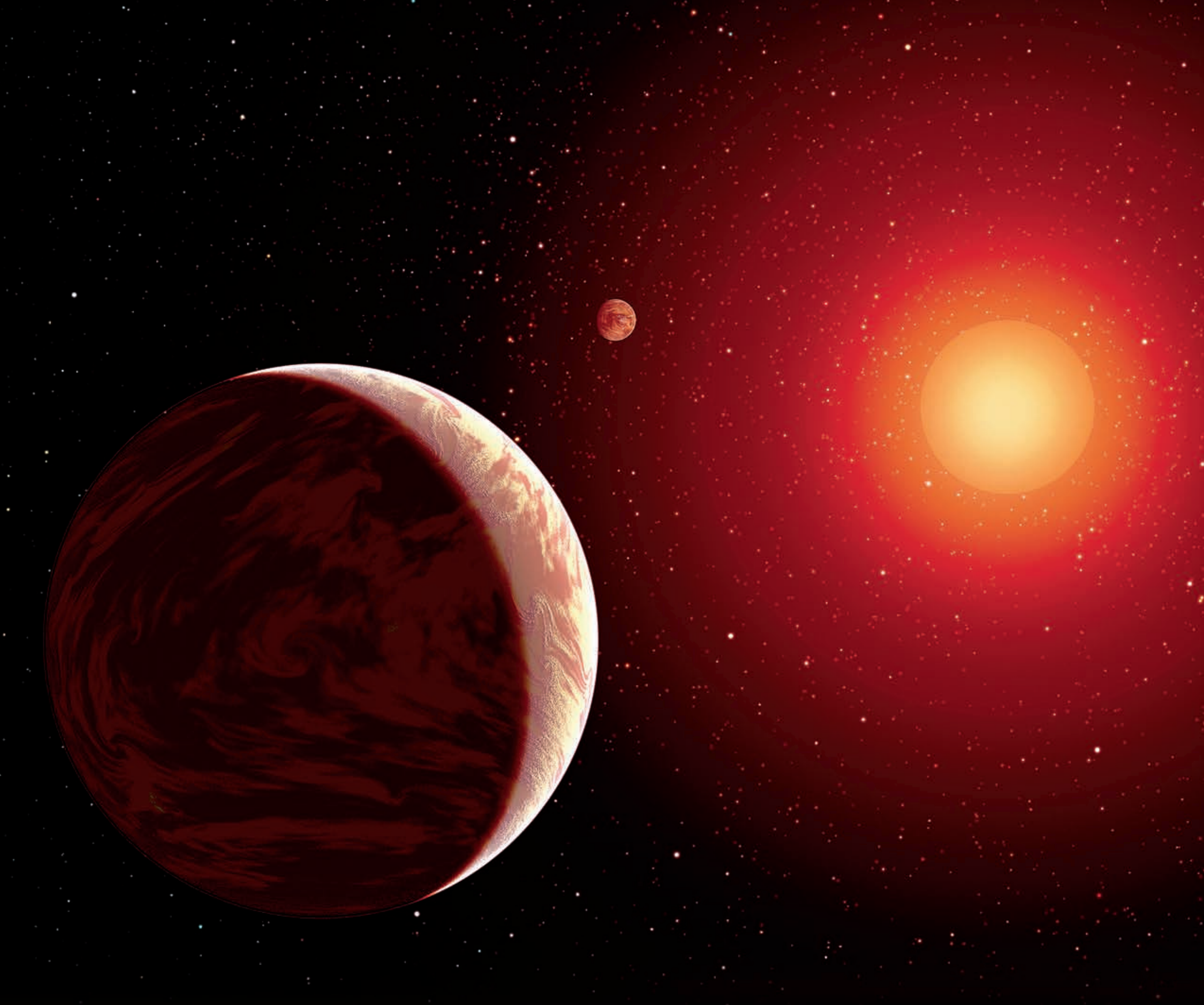
And they are only the beginning, according to astronomers John Johnson and Jonathan Swift, who recently published a paper suggesting that there is about one planet per star throughout the Milky Way: a total of about 100 billion planets. In other words, there are still *plenty* of planets out there for the finding.

The astronomers who do the searching—who are sometimes called exoplanet hunters—are driven by such lofty goals as enhancing human understanding of our place in the cosmos; determining whether we, as a planet or a solar system, are a galactic oddball; learning just how planetary systems form and evolve; and deciding where our sun fits into the spectrum of stars in the galaxy. And yet, at the heart of the field lies the more basic, age-old question, "Are we alone?"

The short answer: no one knows. Still, with every research-packed year it gets increasingly difficult to believe that we are as alone in the cosmos as we once thought we were. As astronomers identify more exoplanets, the sheer numbers—let alone the scale of the universe—point to the possibility that there are other planets out there capable of hosting life.

In the early days of exoplanet studies, all of the newly discovered worlds were gas giants—enormous planets that, like Jupiter, are not primarily solid—that orbit far too close to their host stars to harbor life. As technology and techniques have improved—and with the launch of NASA's planet-hunting, space-based telescope, Kepler—the average size of detected exoplanets has shrunk, with the majority of candidates now two to six times the size of Earth or smaller.

But what astronomers are *really* looking for are rocky planets that are 0.8 to 1.25 times the size of Earth and whose orbits keep them within the region around their host stars, called the habitable zone, where conditions would be right for liquid water to exist.



Such planets, after all, are the ones most likely to be home to some kind of living creature. And, in the interest of follow-up studies, it would be ideal if they were located relatively nearby.

In April, the astronomy world was abuzz with the news that the Kepler mission had detected two planets—one 40 percent, the other about 60 percent larger than Earth—in the habitable zone of a star in the constellation Lyra. Unfortunately, that planetary system is some 1,200 light-years away.

And so, even as the systematic investigation of Mars continues with NASA's Curiosity and Opportunity rovers—not to mention the fleet of satellites circling the planet—and even as we learn more about the potential habitability of moons like Europa and Titan, the reality is that Earth's astronomers and astrobiologists are still working with a statistical sample of one when it comes to worlds known to host life.

Still, there is hope that change is just around the corner and can be reached with a lot of hard work—work that Caltech researchers are right in the thick of. Some of those researchers, like Johnson and Swift, are busy hunting planets. Others, like planetary astronomer Heather Knutson, are characterizing their atmospheres. And then there's the NASA Exoplanet Science Institute (NExScI), an entire center on the Caltech campus dedicated to supporting NASA's Exoplanet Exploration Program missions by—among other tasks—maintaining the Exoplanet Archive, an interactive table of exoplanets both confirmed and not, which is used by researchers around the world.

SHIFTING TARGETS

One of the most exciting discoveries of 2012 came when Johnson's group pinpointed three planets orbiting a red dwarf, a small, rather dim type of star. These planets, named after

Above: An artist's concept depicting three planets orbiting a red dwarf. Caltech astronomers and their colleagues recently discovered such a planetary system orbiting red dwarf KOI-961.

their host star, KOI-961, were not only the first rocky planets ever found around a red dwarf, but were also the three smallest confirmed planets ever detected outside our solar system.

"When we found those three tiny planets it was exhilarating and a huge boost of energy for my group," Johnson says.

Why was it so exciting? Because the team realized that rather than focusing on sunlike stars, as the Kepler mission does, they could look for small, rocky planets around small red dwarfs.

To understand why that's good news, you need to understand that one of the ways astronomers search for exoplanets is called the transit method. It involves watching for tiny dips in the amount of light coming from a star—dips caused by the movement, or transit, of a planet in front of that star. The strength of that signal's dip depends on the size of the transiting planet relative to the size of its host star: the more starlight the planet blocks, the larger the signal.

All of which is to say that if you're looking for stronger, easier-to-detect signals you need either a larger planet or—as is the case with the three tiny planets and their red dwarf—a smaller star.

Red dwarfs make up only about 3 percent of the 150,000 or so stars Kepler has been studying—distant stars in a slice of the Milky Way extending from hundreds to thousands of light-years away. But red dwarfs are thought to account for about 70 percent of all the stars in the galaxy. Which is why Johnson believes our galaxy must be swarming with little potentially habitable planets around faint red dwarfs.

WHERE THE SUN SETS TWICE

Of course, red dwarfs aren't the only stars that are capable of hosting planets teeming with life. Longtime exoplanetary scientist Stephen Kane and postdoctoral scholar Natalie Hinkel have been interested in another type of star system—a so-called circumbinary system, in which an exoplanet orbits more than one star. (Yes, some planets can indeed orbit more than one star, à la the planet Tatooine in *Star Wars*.) They recently showed that many studies trying to calculate the extent of such systems' habitable zones have oversimplified the story by using the parameters of only one star to determine where life might be possible.

"We heard people give talks about circumbinary systems, and we found that they had taken all of the fun out of the problem," Hinkel says. "By knocking the system down to just one star, they took something that's interesting—that has motion and will move and change—and simplified it to the point where it was sort of boring."

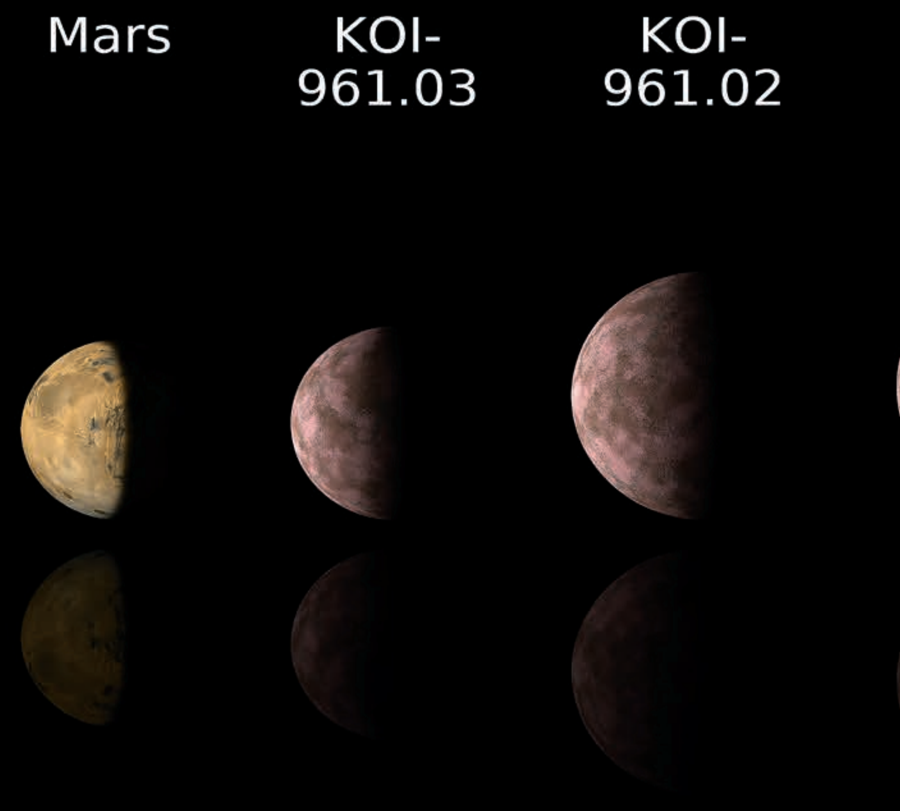
Hinkel and Kane brought back the fun, recalculating habitable zones for a number of planet candidates identified by Kepler in circumbinary systems. In making their reckonings, they took into consideration not only the masses of both stars but things like the brightness of the stars relative to each other and the distance between them. What they found was that looking at both stars often made a significant difference; in one case, for instance, where the two stars were very similar in size, the habitable zone turned out to be peanut-shaped.

Such discoveries will now need to be incorporated into Kane's Habitable Zone Gallery (hzgallery.org), an online database of already-calculated habitable zones, which Kane created and maintains.

But Kane is known for much more than his database. He's become expert in three different exoplanet-detecting techniques over the years: microlensing (which identifies exoplanets through the gravitational light-bending effect they and their host stars can have, magnifying images of perfectly aligned, more distant stars), the transit method, and something called the radial velocity, or Doppler, method, which essentially measures the wobble in a star that is caused by its planets as they orbit. (An orbiting planet actually tugs its star back and forth ever so slightly—a small but measurable effect that can signal a planet's presence.)

"As far as I know, I'm still the only person who has discovered a planet using all three of these techniques," Kane says. "That's my claim to fame."

Kane's range of experiences has shown him not only how to use these individual methods to find planets,



but also how the methods can complement one another. To that end, he's combined his work on radial velocities and transits to predict when planets detected with the radial velocity method will transit their host stars—information that can help other scientists, like Heather Knutson, who aim to characterize those planets.

GETTING DOWN TO DETAILS

Knutson gets information on the size of a planet relative to its star via the transit technique; the radial velocity measurements tell her all she needs to know about the planet's mass. By combining those pieces of information, she can compute a particular planet's average density, which in turn says something about the basic composition of the planet—whether it's mostly gas, mostly rock, or something in between.

To learn even more about a particular planet, Knutson collects another set of measurements when it swings behind its star—an event called a secondary eclipse. By imaging this event at different wavelengths, she can create a spectrum indicating the amount of light emitted by the planet and its atmosphere at particular wavelengths. "Once we have a spectrum, we can start to fit it with different models and try to figure out the details of the composition of the planet," Knutson explains. "It also tells us the temperature of the planet."

Knutson also measures the amount of light coming from the planets during transit events themselves, learning about the molecules present in a planet's atmosphere based on which wavelengths of the star's light are absorbed. "Just the fact that you see absorption at all tells you that the planet must have an atmosphere, and then you can start to ask what kind of atmosphere it is," Knutson says.

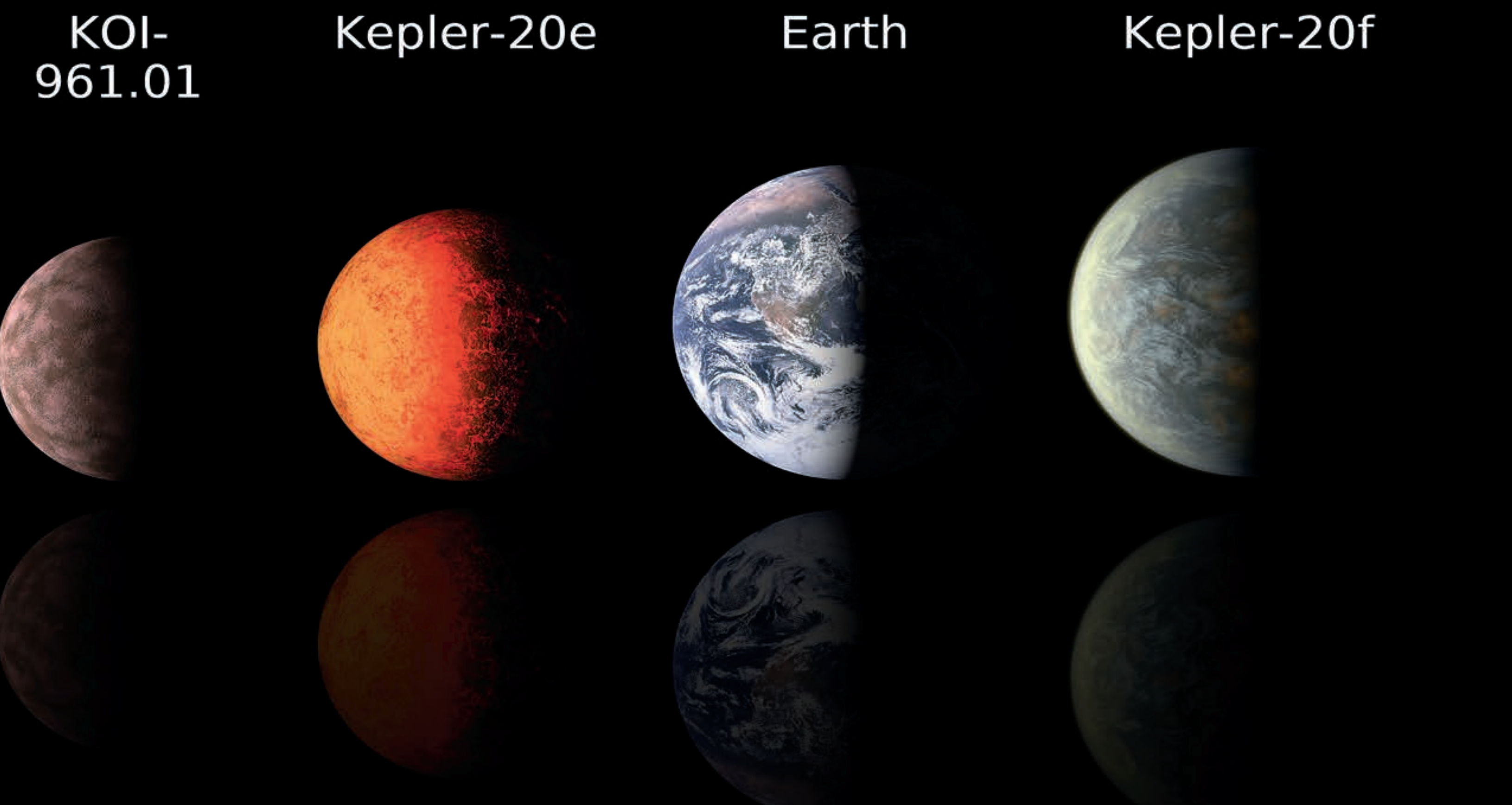
To capture such tiny signals—which require a high level of precision to measure—Knutson has mostly relied on NASA's Spitzer and Hubble Space Telescopes. She and her colleagues are currently using the telescopes to survey large samples of planets—enough to be able to say whether a given type of planet, such as a gas giant, can have a wide variety of properties. "If I tell you that I have a Jupiter-sized planet with a temperature of 1,000 kelvins, do all planets with those properties look exactly the same?" she asks. "Do they have the same amounts of molecules such as methane or water in their atmospheres? Do they all have clouds? Our goal is to learn more about the detailed properties of these planets, beyond the simple classifications of 'rocky' or 'gas giant.'"

THE DIRECT ROUTE

Lynne Hillenbrand and her colleagues are seeking answers to the same types of questions, but are approaching the problem in a different way, using an advanced imaging system dubbed Project 1640 (in honor of a representative wavelength, in nanometers, at which the instrument collects measurements). Project 1640 was designed especially for the Hale Telescope at Palomar Observatory and allows astronomers to directly collect broad spectra of nearby exoplanets even if they are not transiting their host stars.

After nearly a decade of development, Project 1640 started its survey—slated to run for three years—in June 2012 and quickly proved itself by collecting the spectra of four previously known planets orbiting the star HR 8799, which is some 128 light-years away. Those worlds are five to 10 times the mass of Jupiter, and compared to the planets that have been detected via the radial velocity or transit methods, they orbit farther from their host star, which makes them more like the gas giants in our solar system.

Above: This chart compares several small exoplanets to Earth and Mars. When three worlds orbiting red dwarf KOI-961 were reported on in early 2012, they were the smallest known exoplanets. Kepler-20e and Kepler-20f were the first Earth-size exoplanets ever found. None of the pictured exoplanets lie in the habitable zone of its central star.



"Imaging techniques like ours are most sensitive to objects that are farthest away from the star because of the necessary contrast," Hillenbrand explains. "We need to block out the light from the bright, glaring star, which can be more than a million times brighter than the planets we are looking for around the youngest stars."

The overall design concept is based on an idea that Ben Oppenheimer (PhD '99) of the American Museum of Natural History first developed for the U.S. Air Force AEOS telescope in Maui. The setup at Palomar, which was translated from this original idea, relies on the larger Hale Telescope and its sophisticated new adaptive optics system, which minimizes the blurring effects of Earth's atmosphere on its observations. Engineers at JPL have even built an additional back-end piece of hardware to further refine those antiblurring corrections and control diffracted and scattered light. At the heart of the instrument, however, is a coronagraph—a sophisticated device that blocks the light from the star—as well as a spectrograph that splits the remaining light into 40,000 individual spectra from the postcoronagraph image. Finally, two software packages process the spectra and pull out any signals of planet-like objects.

Over the next few years, Project 1640 will survey 200 or so nearby stars hotter than the sun to see if it can detect and characterize undiscovered exoplanets. Eventually, astronomers would like to get to the point where a similar system could obtain spectra for planetary objects that are the mass and size of Earth. "So there's a long way to go," Hillenbrand says.

However far that may be, all exoplanet researchers are working toward a common goal: a greater understanding of what lies beyond our own solar system. How many planets are there? How and when did they form? What do their spectra look like? Which of them might be habitable? And what, then, does all that information say about the formation and evolution of home sweet home? The vast number of remaining questions might seem daunting, but as Knutson explains, that's part of the allure when you're an astronomer.

And that, she and her colleagues agree, is what makes being a planet hunter so stimulating. "We think we know something about planets," Knutson says, "but we're constantly being surprised by the results of our observations. That's good, because it means that there are always new questions to tackle." E&S

Lynne Hillenbrand is a professor of astronomy.

John Johnson is an assistant professor of planetary astronomy. His work is funded by the David and Lucile Packard Foundation and the Alfred P. Sloan Foundation.

Stephen Kane is a research scientist with NExScI.

Heather Knutson is an assistant professor of planetary science. She is currently funded by JPL-Caltech and by NASA via the Space Telescope Science Institute.

Caltech alumni continue to pursue their own big questions long after earning their degrees. Here are the questions that inspired six of our graduates as they helped to shape our world, and that led them to be named recipients of this year's Distinguished Alumni Awards.

Questions of a

Is there a quantitative theory of computation?

Juris Hartmanis (PhD '55)

In mathematics, there is a classic puzzle involving a traveling salesman who must crisscross the country to make calls in numerous cities. What is the most efficient route?

"This problem is good for a computer because it requires mathematical brute force," says mathematician Juris Hartmanis.

But can you figure out how hard the problem is or, more specifically, how long it will take you to calculate the answer—*before* attempting to do so?

In 1965, Hartmanis and research partner Richard Stearns proved that you could when they established classes of computational complexity and introduced the time-hierarchy theorem, which describes exactly how a machine, given more time, can solve more problems. The paper earned the pair a Turing Award for helping to establish computer science as a formal discipline.

Hartmanis admits that there was one thing he did not calculate: "I could not have predicted how quickly computers would change the world around us."

Can personal obstacles help define a career?

Y. C. L. Susan Wu (PhD '63)

When Susan Wu became the first woman to earn a doctorate in aeronautics from Caltech, she knew little about magnetohydrodynamics (MHD), a way to achieve propulsion or produce electricity without the use of moving parts. She got into the field, she says, for the health care: during her last year of studies, Wu was diagnosed with a heart condition requiring surgery. "Only one company offered insurance that would cover the 'preexisting condition' procedure," Wu says. "So I began my professional career with them, researching MHD."

The oil crisis of the 1970s spurred a boom in alternative-energy research, and Wu became a recognized expert in the field. Then, in 1988, at the age of 55, she decided to start her own company—ERC Inc.—an engineering company focused on her first love, aerospace and defense research. ERC currently employs more than 700 people in five states. Now retired, she and husband James Wu (MS '59, PhD '65) are passionate advocates for education.

Wu's achievements demonstrate that she's uncovered at least one new source of alternative energy—herself.

Can we understand the process of combustion?

Sébastien Candel (MS '69, PhD '72)

Part of what makes the process of combustion so complex has to do with the nature of turbulence. Fast reactions and intense chemical conversion complicate the picture even more.

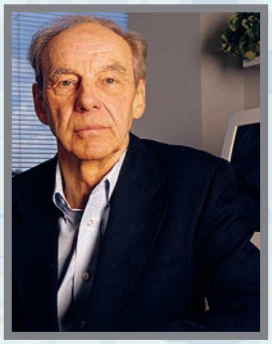
"It turns out that, particularly with combustion, engineers are pretty good at building things that work," says Sébastien Candel, who has spent his career studying aerospace sciences with a focus on combustion. "But we just don't always fully understand why."

Candel, through his research and his leadership of the mechanical and aerospace studies program at École Centrale Paris, has made significant contributions to combustion science through a combination of analyses, computational models, and experiments.

"I continue to be fascinated by these complex interactions," Candel says, "and by finding better ways to harness them."




Lifetime

Clockwise from left: Sébastien Candel, Y. C. L. Susan Wu, Stephen Wolfram, James R. Fruchterman, Juris Hartmanis, Uma Chowdhry

Can new materials help us build a better world?

Uma Chowdhry (MS '70)

While at Caltech in the late 1960s, Uma Chowdhry was inspired by metallurgy expert Pol Duwez to investigate the emerging field of materials science—the study of substances such as metals, plastics, or ceramics in order to create new materials with superior properties.

This early motivation led to a long career at DuPont, where Chowdhry researched superconducting oxides and new ceramic materials, eventually rising to become the company's chief science and technology officer—the first female to be named to that role at a Dow 30 company. Her global research and development strategy helped the corporation push into emerging scientific fields and expand into countries with developing economies.

"We live in an exciting time," Chowdhry says. "We have vast opportunities to use the versatility of renewable materials and our understanding of chemistry, biology and materials science in new and unique ways to create a sustainable tomorrow."

Is the universe just one large computer program?

Stephen Wolfram (PhD '80)

When describing his work, Stephen Wolfram often begins with an illustration in which a collection of very basic computer programs—which he calls "cellular automata"—are given a set of rules and then sent out like worker bees to construct an image resembling a pyramid. With only slight variations to their coding, however, it turns out that the automata will create something wildly more complex.

"It came as a huge shock," Wolfram confesses. "A very simple program can produce a pattern too complex to predict. The only way to find its outcome is to watch it evolve."

Wolfram realized that simple systems could execute sophisticated calculations and used his discovery as a building block to create the software program Mathematica, now considered one of the standard environments for algorithmic computation.

He theorizes that the complexity found in nature may be the result of elementary systems like his automata. Says Wolfram: "I believe this has deep implications for issues such as biological processes, economies, and artificial intelligence."

Can our discoveries help to improve lives?

James R. Fruchterman (BS '80, MS '80)

It was a Caltech lecture on weapons systems—in particular, an optical target-recognition system to guide missiles—that steered James Fruchterman toward a life of philanthropy. "I went back to my dorm room and thought, 'How could we use that technology for something a little more benign?'" he remembers.

His idea: a text reader for the blind. Years later, his dream became a reality when he founded a nonprofit, Arkenstone, and began building reading devices using a breakthrough optical text-recognition technology that he had helped develop.

Having proven that technology could be used to help the disabled, Fruchterman was hooked. In 2000, he founded Benetech, a nonprofit focused on developing technology to address social needs in areas like global literacy, human rights, and the environment.

"Engineers and inventors are problem solvers who want their work to be relevant," he says. "If we can measure our endeavors by the lives we improve, then we can truly say we're successful."

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David G. Goodwin
1957–2012

David G. Goodwin, professor of mechanical engineering and applied physics, emeritus, passed away on November 11, 2012, after a five-year battle with brain cancer and a struggle with Parkinson's disease that began in 1998. He came to Caltech in 1988 as an assistant professor of mechanical engineering, was promoted to associate professor of mechanical engineering and applied physics in 1993 and professor in 2000, and retired in 2011.

Goodwin was best known for developing ways to grow thin films of high-purity diamond. Diamond films—transparent, scratch-resistant, and efficient dissipaters of the heat generated by high-powered computer chips—are now routinely used to protect electronic and optical components, and diamond-coated drill bits can be found at any hardware store.

But the diamond work was just one facet of Goodwin's research. According to longtime collaborator David Boyd, once a postdoc of Goodwin's and now a Caltech staff member, "Dave's real passion was modeling. He felt that he never fully understood something unless he could model it. He had a keen insight into how things work. He would proffer an oftentimes very simple explanation that captured the essential physics, and he was able to see how that applied in engineering terms. It's really unusual for an engineer to know that much physics, or a physicist to have that much engineering."

In his spare time, Goodwin was an accomplished guitarist, a skilled woodworker who made several pieces of furniture for the family's Craftsman house, and a prolific painter in oils.

Goodwin is survived by his parents, George and Verma Goodwin; his sisters, Ellen Goodwin Levy and Jennifer Goodwin Smith; his wife, Frances Teng; and his children, Tim and Erica.

To learn more about David Goodwin's life and work, visit http://www.caltech.edu/content/caltech-mourns-passing-david-g-goodwin.

In honor of our Big Questions issue, we asked our alumni the biggest question of them all: **WHAT IS THE MEANING OF LIFE?** Here is what some of them had to say.

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Family, friends, and society with dance, art, and music are the meaning of life. Science, medicine, and history are the means of *making life better.*

To enjoy living . . . and to do so **SUSTAINABLY** so that future generations can enjoy it as well.

Life is the **ebb and flow of energy and electrons.** What is meaningful is to discover nature's secrets of how energy and electron flow are regulated and controlled.

To love and serve God in this life, and to be happy with Him forever in the next.

Life is a **spacesuit** for your DNA.

Perhaps an answer lies in the question, *"What is a life of meaning?"*

I am certain it has something to do with both the **Millikan pumpkin-drop flashes** and the **Ride.**

Try and be nice to people, avoid eating fat, read a good book every now and then, get some walking in, and try and live together in **peace and harmony with people of all creeds and nations**.

—Monty Python's *The Meaning of Life*

Chocolate, duh!

To **LOVE AND TO BE LOVED.** Nothing else comes close.

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