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Engineering & Science

The
Future
According to

Caltech*ers*



Caltech

VOLUME LXXIX, NUMBER 2, SUMMER 2016



Engineering & Science

VOLUME LXXIX, NUMBER 2, SUMMER 2016

2 Caltech on Social Media

4 Random Walk

Mighty Diatoms • Warring Robots • Social Hormones • And More

11 Origins

Helping Add Extra to Curricular: The History of the Caltech Y

12 “The Universe Has Spoken”

BY KIMM FESENMAIER

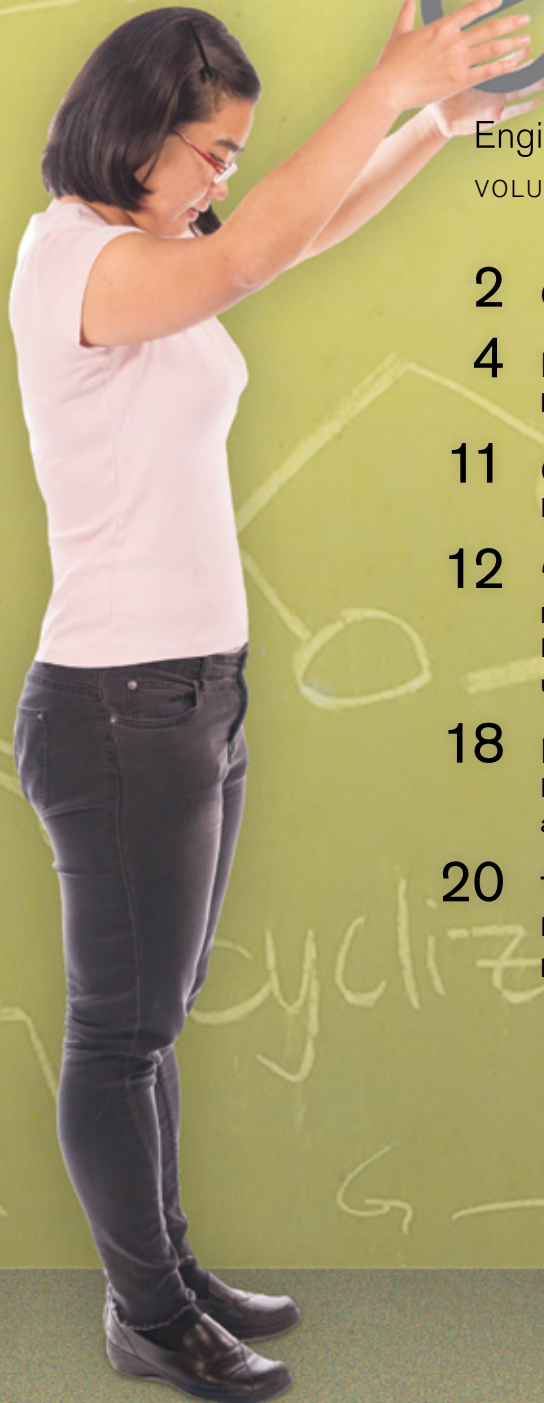
How Caltech researchers used numerical relativity to help understand the ripples in spacetime predicted by general relativity.

18 Nine Things to Know About Planet Nine

From its mass to its orbit, here are some of the things Caltech astronomers are finding out about Pluto's possible replacement.

20 Threading the Needle

Biologist David Baltimore talks about the abundant promise and potential perils of the gene-editing technique CRISPR-Cas9.



24 Special Delivery

BY MARK WHEELER

Whether they're landing rovers on Mars, collecting data in hard-to-reach locales, or shepherding drugs to the brain, Caltech researchers are thinking about transportation in unexpected ways.

30 The Next Big Thing

BY NEHALY SHAH

The future is bright for those about to become Caltech's newest alumni, who talked to us about the big ideas they'll be pursuing next.

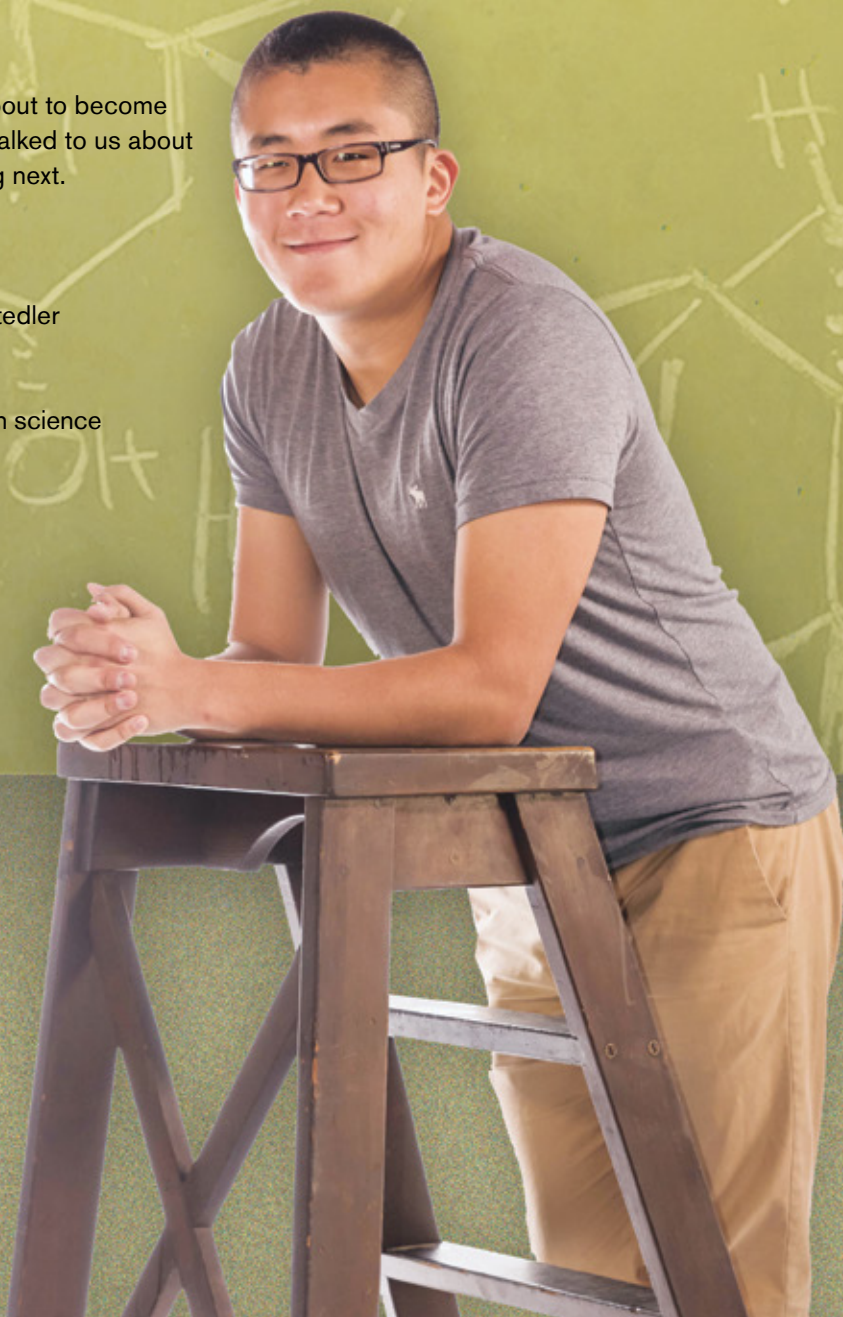
35 In Memoriam

David G. Harkrider

The Honorable Shirley M. Hufstedler

36 Endnotes

What will be the next big thing in science or engineering?



Caltech on Social Media

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



@amoration Good thing about living near @Caltech = students edit #STEM textbooks on the bus and ask for feedback #nerdlove



@Atul_Gawande Getting to give @Caltech's 2016 Commencement Address and aim to learn their plans for when the robots take over.



@gravitate_to_me Filming multiple episodes for the Discovery Channel's "How the Universe Works" today at @Caltech. Great weather and interesting wildlife too



@IndivCollective That moment when you ask your #astrophysicist mother about #gravitationalwaves and she sends you an "easy to read" article from #Caltech



@Miquai Overheard at @Caltech: "It's practically an Avery away!" Avery is now a unit of distance (equal to walk from S. Houses to Avery), it seems.



@estrellascafe Cute @Caltech turtle striking a pose (or telling me to go away)

Tweets and Instagram comments may have been edited for spelling and grammar.

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breakthrough

THE CALTECH CAMPAIGN

Break Through is an ambitious \$2 billion philanthropic initiative that will provide Caltech's remarkable scholars and inventors with resources to discover and innovate for generations to come.

The campaign will raise funds to support three key objectives:

- **Enable Caltech to take smart risks:** Flexible funding empowers Caltech to attack important problems and pursue promising opportunities wherever they may lead.
- **Provide an exceptional educational experience:** Fellowships, scholarships, and funds to bolster student life, teaching, and outreach help prepare Caltech students to change the world.
- **Seed and support high-impact research areas:** Caltech is poised to make revolutionary contributions in areas such as exploration of the universe, science and technology for human health, computation across fields, and energy and the environment.

"People come to Caltech to change the world," says Caltech president Thomas F. Rosenbaum, holder of the Sonja and William Davidow Presidential Chair and professor of physics. "The *Break Through* campaign will help ensure that Caltech's culture of excellence, fearlessness, and ambition will thrive far into the future, both creating knowledge for the ages and improving lives today."



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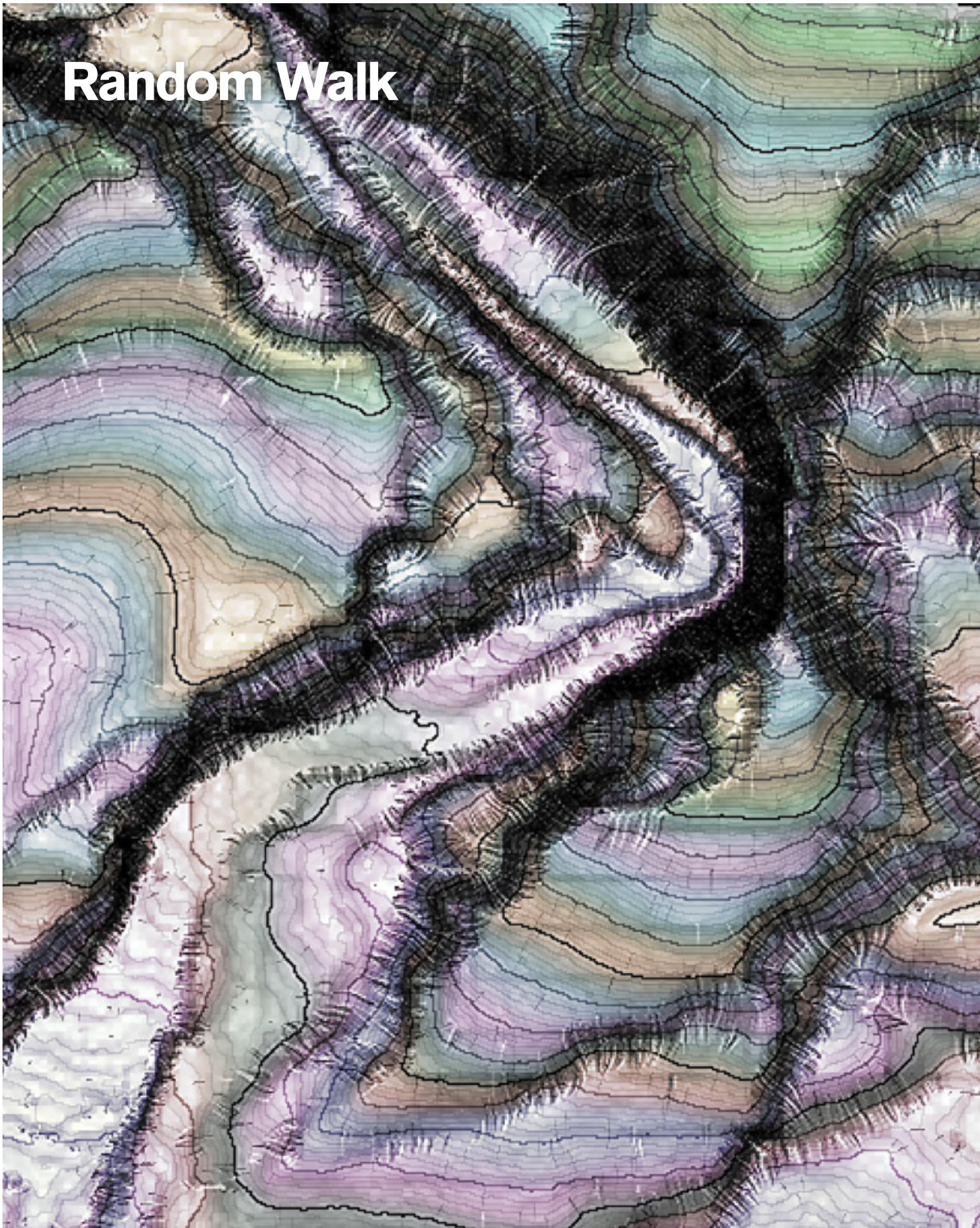


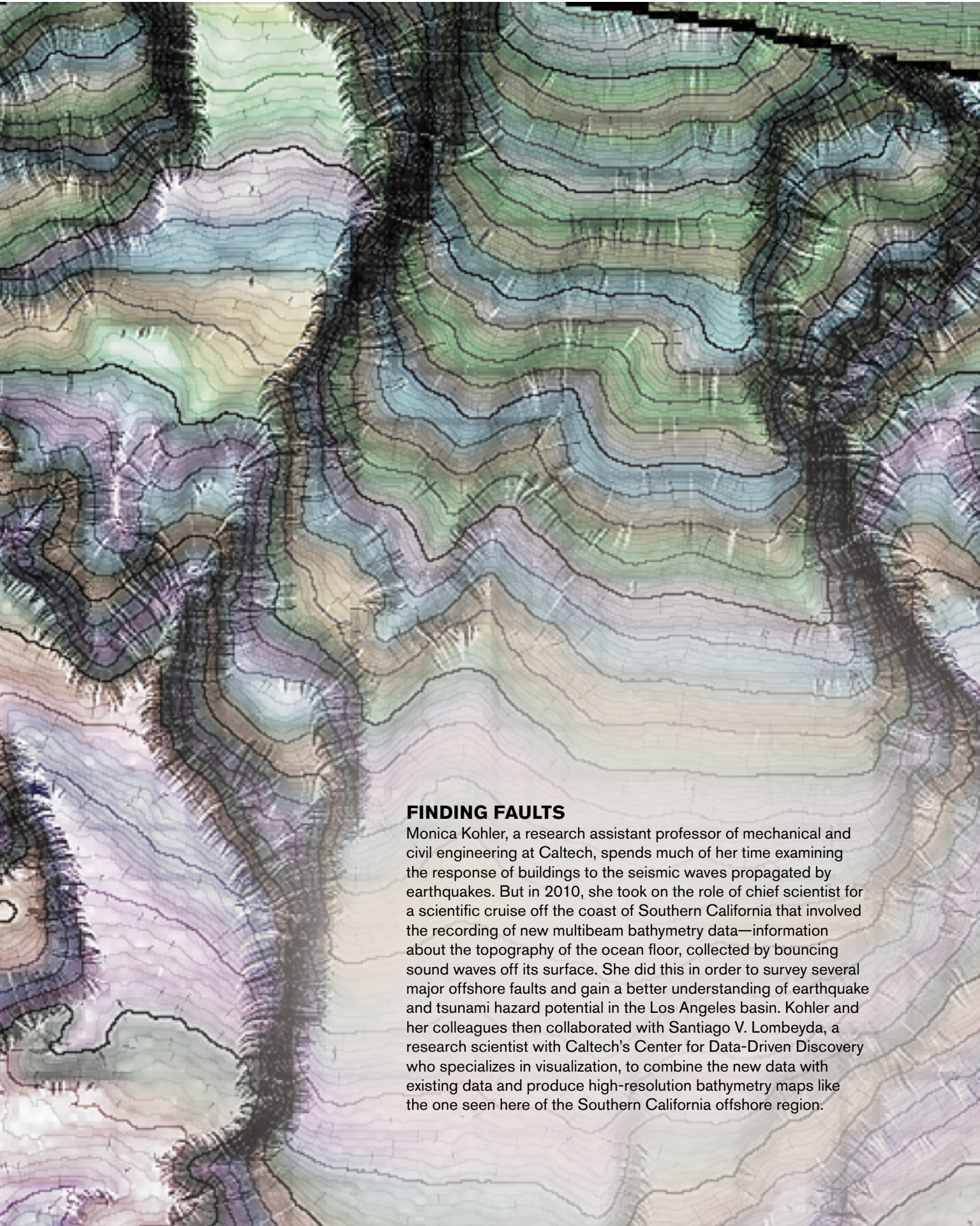
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Professor of History

Random Walk





FINDING FAULTS

Monica Kohler, a research assistant professor of mechanical and civil engineering at Caltech, spends much of her time examining the response of buildings to the seismic waves propagated by earthquakes. But in 2010, she took on the role of chief scientist for a scientific cruise off the coast of Southern California that involved the recording of new multibeam bathymetry data—information about the topography of the ocean floor, collected by bouncing sound waves off its surface. She did this in order to survey several major offshore faults and gain a better understanding of earthquake and tsunami hazard potential in the Los Angeles basin. Kohler and her colleagues then collaborated with Santiago V. Lombeyda, a research scientist with Caltech's Center for Data-Driven Discovery who specializes in visualization, to combine the new data with existing data and produce high-resolution bathymetry maps like the one seen here of the Southern California offshore region.

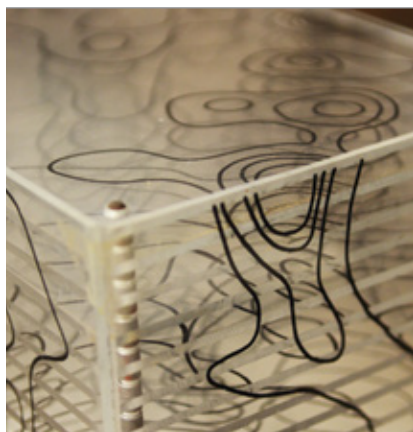
“The greatest gift you can give someone is to share your understanding with them and to help them develop their own understanding. That incredible connection between the way you appreciate the complexity of the world and the way you can give students the tools to see things that you never saw before—it’s really beautiful.”

—Ellen Rothenberg, the Albert Billings Ruddock Professor of Biology and winner of 2016 Richard P. Feynman Prize for Excellence in Teaching, commenting on what she enjoys most about being a professor



She **SHOOTS**, She **SCORES**, She **BREAKS A RECORD!**

Senior Stephanie Wong became the Caltech women's basketball program's all-time leading scorer in a game against Whittier College on January 26. Wong, a chemistry major, tied and surpassed the 1,241-point benchmark set by Lindsay King (BS '08) on a pair of free throws just before the end of the third quarter. By the end of the season, Wong had amassed 1,333 career points. She also holds the program record with 231 career three-pointers, as well as the single-game record for three-pointers (seven), a feat she accomplished twice.



On the Grounds

This model of a three-dimensional Patterson map of the amino acid hydroxy-L-proline was constructed in the early 1950s. The map was used to obtain the structure of the molecule from X-ray photographs of a crystal of the compound. When X-rays are scattered by crystals, the amplitudes of the X-rays can be readily measured but not their phases. Both are needed to calculate an electron density map, which indicates where the atoms are; a Patterson map is a way to solve this phase problem. The model is one of the first, if not *the* first, construction and interpretation of a three-dimensional Patterson function. So where does this little piece of history reside?

Answer: The model can be found in Caltech's X-Ray Crystallography Facility in the Beckman Institute.

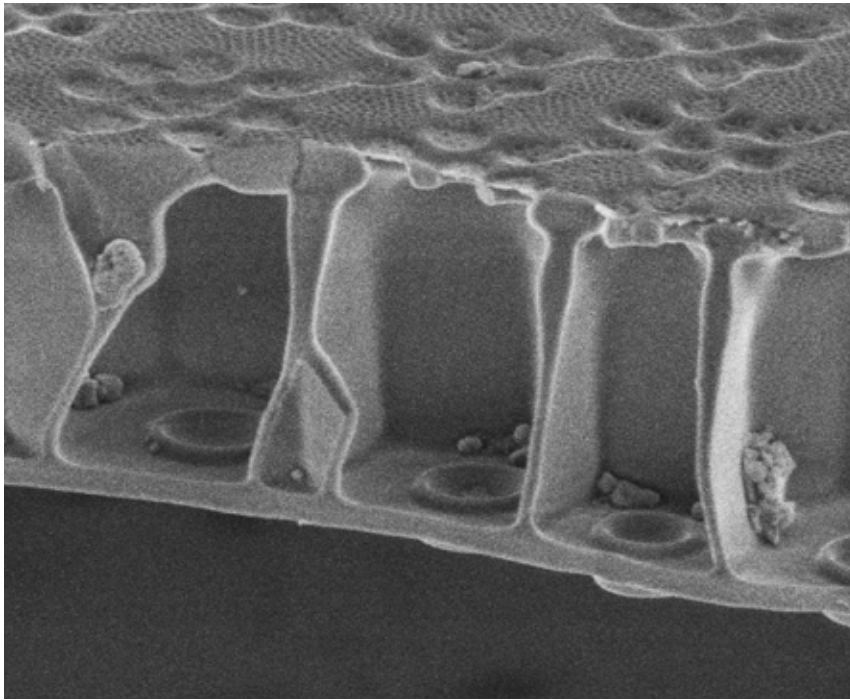
TINY DIATOMS BOAST ENORMOUS STRENGTH

Diatoms are single-celled algae, around 30 to 100 millionths of a meter in diameter, that are ubiquitous throughout the oceans. These creatures are encased within a hard shell shaped like a wide flattened cylinder—like a tambourine—that is made of silica. Researchers in the lab of Julia Greer, professor of materials science and mechanics in Caltech's Division of Engineering and Applied Science, have found that these shells have the highest specific strength—the strength at which a structure breaks with respect to its density—of any known biological material, including bone, antlers, and teeth. The findings were published in the *Proceedings of the National Academy of Sciences* in February.

The shell, or frustule, of a diatom is porous, perforated by a honeycomb-like pattern of holes. There are several theories about the function of these intricate shell designs, including that they evolved to control fluid flow, for example, or to help the organisms acquire nutrients. Greer and her group propose that the holes also act as stress concentrators—“flaws” in the material that can suppress the propagation of cracks, which would lead to failure of the entire organism.

“Silica is a strong but brittle material. For example, when you drop a piece of glass, it shatters,” says Greer. “But architecting this material into the complex design of these diatom shells actually creates a structure that is resilient against damage. The presence of the holes delocalizes the concentrations of stress on the structure.”

The group plans to use design principles from diatoms to create resilient, bioinspired artificial structures. —LD



The structure of this silica shell allows the diatom to maintain high strength while keeping weight low. Combining this architecture with a silica-organic composite as the constituent material gives the diatom shell the greatest strength-to-weight ratio of all previously reported natural biological materials.



New JPL Director Named

Michael M. Watkins, the Clare Cockrell Williams Centennial Chair in Aerospace Engineering and Director of the Center for Space Research at The University of Texas at Austin, has been appointed director of the Jet Propulsion Laboratory and vice president at Caltech.

Watkins will formally assume his position on July 1, 2016. He succeeds Charles Elachi, who will retire as of June 30, 2016, and move to the Caltech campus as professor emeritus.

Watkins is an internationally recognized scientist and engineer. Prior to assuming his current position at The University of Texas in 2015, he worked at JPL for 22 years, where he held leadership roles on some of NASA's highest-profile missions. Watkins served as mission manager and mission system manager for the Mars Science Laboratory Curiosity Rover; led review or development teams for several missions including the Cassini, Mars Odyssey, and Deep Impact probes; and was the project scientist leading science development for the GRAIL moon-mapping satellites, the GRACE Earth science mission, and the GRACE Follow-On mission, scheduled for launch in 2017. He last served at JPL as manager of the Science Division, and chief scientist for the Engineering and Science Directorate.

“Michael's record of successful mission leadership and impressive management skills quickly distinguished him as a leading candidate for this position,” says Caltech president Thomas F. Rosenbaum, the Sonja and William Davidow Presidential Chair and professor of physics. “As JPL director, Michael will build upon the laboratory's outstanding achievements in planetary exploration and earth science, strengthening the connections between Caltech's campuses and partnering with NASA to deliver highly complex and nuanced missions.”

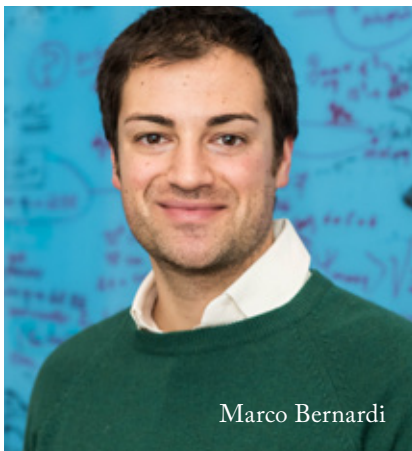
Honoring a Visionary

On February 26, more than 1,000 people gathered in Beckman Auditorium to hear exceptional researchers, including five Nobel laureates, consider our future as part of the full-day Science and Society conference that honored the career of Ahmed Zewail (right), Caltech's Linus Pauling Professor of Chemistry, professor of physics, and director of the Physical Biology Center for Ultrafast Science and Technology. Zewail, who has served on Caltech's faculty for 40 years, was the sole recipient of the 1999 Nobel Prize in Chemistry for his pioneering work in femtochemistry, the study of chemical reactions on extremely short timescales.

To further honor Zewail, Caltech presented him with a rare book of Benjamin Franklin's speeches and scientific research. Caltech Provost Ed Stolper noted that the gift is a fitting one for Zewail, who has come to embody the ideal of Caltech, a place "where scientists and engineers are limited only by their imagination." He added that Ahmed is one of the few scientists who, like Benjamin Franklin and Linus Pauling, not only excelled in science but has made a broader impact on society through his writings and actions.



FACULTY FOOTNOTES



Marco Bernardi

All materials are composed of a tiny universe of particles—from the physical ones, like electrons and atomic nuclei, to the excited states (or so-called quasiparticles) that constantly collide and bounce, gaining and losing energy. Marco Bernardi, a newly appointed assistant professor of applied physics and materials science in the Division of Engineering and Applied Science, is fascinated by these interactions and how they give rise to the world around us.

"We study the collision processes between these excited states, both to understand the fundamental science and because they are essential for applications," says Bernardi. "These processes take place on a femtosecond timescale—a femtosecond is a millionth of a billionth of a second—so they are very challenging to study experimentally. If we can understand

the timescale for the interactions among electrons, phonons, light, defects, spin, and other excited states, we can predict how materials transport electricity and heat, emit and absorb light, and convert energy into different forms. Applications in electronics, optoelectronics, ultrafast science, and renewable energy abound."

Here are a few more fun facts about Bernardi:

► **He's excited about the emphasis on fundamental science at Caltech.**

"To compute what I'm trying to look at, we have to first build our understanding on simple experiments and materials before we are able to tackle materials at the frontier of condensed matter research. Nobody really wants to do basic measurements on pieces of silicon or gold. But fundamentally we don't know how to compute in detail basic excitations in materials. Caltech supports this kind of science. And no matter what you're working on, you can talk to somebody who will give you some unique perspective or insight."

► **He holds a world record.** "Carbon nanotubes can be either metallic or semiconducting—a material where you can control how much current can flow through—so you should be able to create all kinds of parts of a device just made out of these tubes. During my PhD work at MIT, my adviser and I predicted that it would be possible to create a solar cell entirely out of carbon nanotubes. We worked together with a colleague who synthesized the device from our design, and now we have the world record for making a solar cell entirely out of carbon."

► **He has a travel bug.** "I like to pick a country, go online and find all kinds of options for routes and itineraries, and go explore for two weeks. If I weren't doing science, I would probably be traveling and learning languages and talking to people. My maps tell me that I currently have seen 20 percent of the whole world—on land, that is. My ambition is to get to 80 percent one day."

Social Hormone Promotes Cooperation in Risky Situations

A hormone implicated in monogamy and aggression in animals also promotes trust and cooperation in humans in risky situations, Caltech researchers say.

The findings, published in the *Proceedings of the National Academy of Sciences*, could prove useful for helping groups cooperate. Previous research showed that in males the hormone arginine vasopressin (AVP) promotes monogamous pair bonding and parental behavior but also aggression. “Part of the dark side of monogamy is that an AVP-pumped-up male is more likely to behave aggressively toward intruders,” says study coauthor Colin Camerer, the Robert Kirby Professor of Behavioral Economics at Caltech.

In the new study, Camerer and his team tested the hypothesis that AVP might also play a role in social bonding

in people and could help explain our species’ cooperative tendencies.

The experiment showed that players who received AVP (via a nasal spray) before a group-collaboration game were significantly more likely to cooperate than those who received the placebo. “By targeting a specific hormonal system in the human brain, we could manipulate people’s willingness to cooperate and help them do better,” says Gideon Nave, a graduate student in Camerer’s lab and a coauthor on the study.

To better understand the neural mechanism underlying AVP’s effect on risky cooperation, the researchers conducted the same experiment but this time had subjects—a separate group of 34 men—play the game while their brains were being imaged using a functional magnetic resonance imaging

scanner. The scans indicated that after AVP administration, a part of the brain’s reward system known as the ventral pallidum—a region that is known to have an abundance of AVP receptors—showed a change in neural activity when the players decided to cooperate.

Could the discovery that AVP increases the likelihood of risky cooperation have practical applications and be used, for example, to engender trust and foster cooperation in groups? Perhaps.

“You could imagine a high-stakes situation, such as a military operation, in which people have to trust each other to all do something difficult and it fails if anyone chickens out,” Camerer says. “In that case, you might want to administer AVP to help ensure that everyone is cooperative.” —KT

TriDroid Cup

Caltech’s 31st Annual Engineering Design Competition for undergraduate students in the famed ME 72 course kicked off in Brown Gym on March 8.

This year, students had to design, build, and operate under manual and/or autonomous control a team of three robotic vehicles to play a droid-friendly game of soccer.

Robots were tasked with collecting balls, depositing them into goals, and defending their own goals. Team “Blitzkreig Bots” (pictured from left: Hannah Walsh, Juliane Preimesberger, Tomas Tussie, Michael Jensen, and Cole Allen) took home the top prize for most points scored.



A NEW *TWIST* ON THE HISTORY OF LIFE

For more than a century, paleontologists including Charles Darwin have debated whether the so-called Cambrian explosion—a rapid period of species diversification that began around 542 million years ago—was the equivalent of an evolutionary “big bang” of biological innovation or just an artifact of the incomplete fossil record.

In a recent study, a team of researchers including Joseph Kirschvink (BS, MS '75), Caltech's Nico and Marilyn Van Wingen Professor of Geobiology, and Ross Mitchell, a former postdoctoral scholar in geology at Caltech who is now at Curtin University in Australia, describes a new model showing that during the Cambrian “true polar wander”—an event involving the wholesale relocation of Earth's continents 520 million years ago—most continents would have moved toward the equator instead of toward the poles.

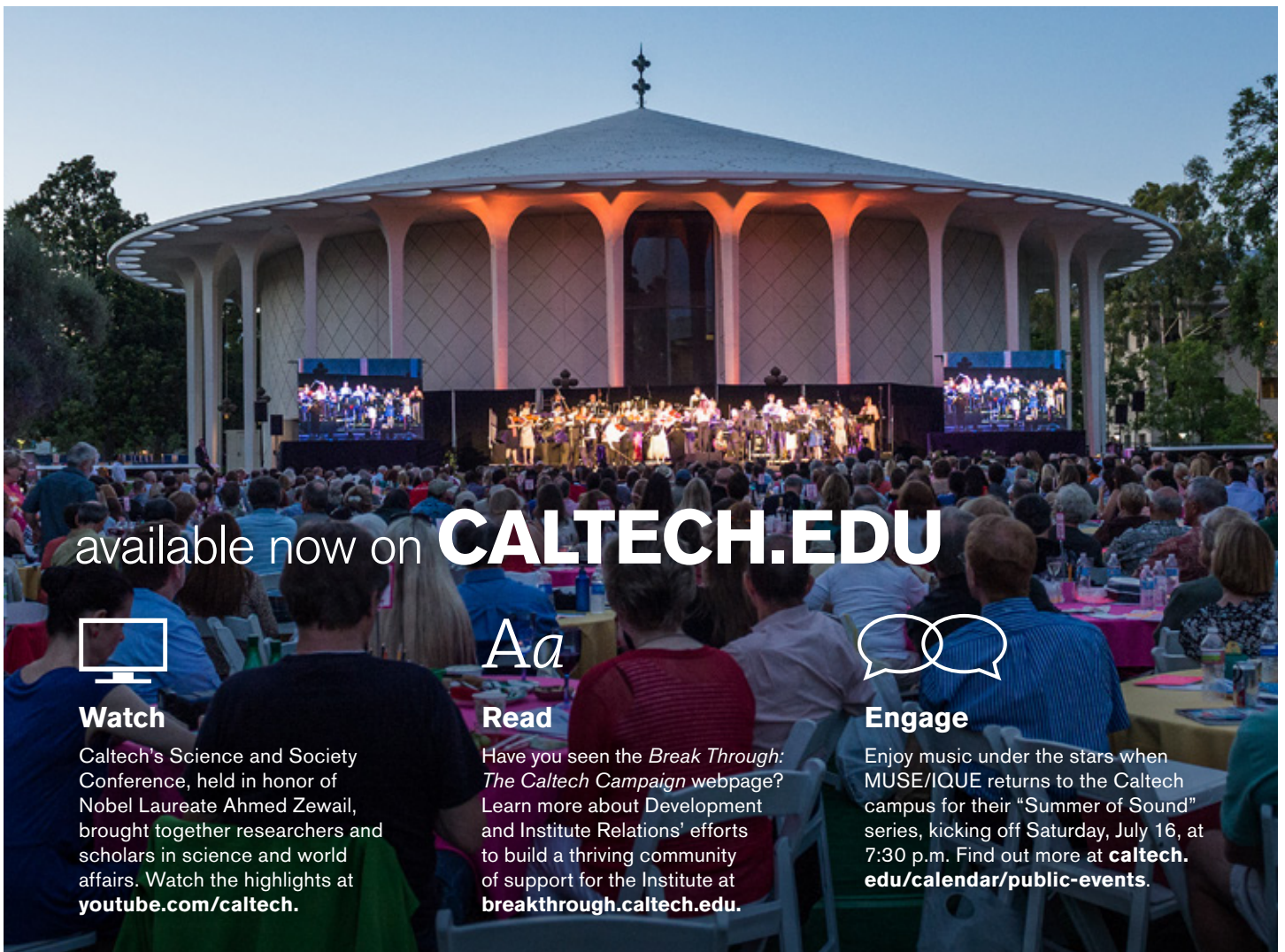
“It's long been observed that biological diversity is highest in the tropics, where nutrients and energy tend to be abundant,” says Kirschvink. “One of the side effects of true polar wander is that sea level rises near the equator but falls near the poles, so the equatorial migration of most Cambrian land masses would have enhanced diversification into previously lower-diversity environments.”

Using a model they developed, the team simulated the pattern of continental migration during the Cambrian and found that their results can explain the distribution of Cambrian fossils.

“Our model provides an explanation for why the fossil record looks the way it does, with many Cambrian fossil groups on some continents but few on others,” says study coauthor Tim Raub (BS, MS '02), a lecturer at the University of St. Andrews in Scotland.

“The same sea-level rise that flooded those continents that shifted to the tropics and opened new ecological niches for faster speciation also led to more fossil preservation,” Mitchell says. “In contrast, the few areas that shifted to the poles became less biologically diverse and also lost rock volume to erosion following sea-level drops due to true polar wander.”

The scientists say their new findings could help resolve the debate started so long ago by Darwin. If their theory is correct, the Cambrian explosion is both a true and dramatic pulse of biological innovation and an expression of preferentially preserved shells on selectively submerged continental margins capable of containing fossils. —KT



available now on **CALTECH.EDU**



Watch

Caltech's Science and Society Conference, held in honor of Nobel Laureate Ahmed Zewail, brought together researchers and scholars in science and world affairs. Watch the highlights at youtube.com/caltech.



Read

Have you seen the *Break Through: The Caltech Campaign* webpage? Learn more about Development and Institute Relations' efforts to build a thriving community of support for the Institute at breakthrough.caltech.edu.



Engage

Enjoy music under the stars when MUSE/IQUE returns to the Caltech campus for their “Summer of Sound” series, kicking off Saturday, July 16, at 7:30 p.m. Find out more at caltech.edu/calendar/public-events.

HELPING ADD EXTRA TO CURRICULAR: The History of the Caltech Y

For the past 100 years, the Caltech Y—an independent nonprofit formally affiliated with Caltech—has played a large role in the enrichment of student life. New Student Orientation, the *little t* freshman handbook, volunteer opportunities, and many lecture series, among a variety of other events and traditions, all started at the Y. To celebrate a century of the organization's positive influence on campus, we look back at how it all started, according to an excerpt from a booklet written for the Caltech Y's 75th anniversary in 1991.

On the evening of October 1, 1916, eleven students of the Throop College of Technology met to discuss the possibility of organizing a Young Men's Christian Association chapter on campus. They wanted to introduce a sense of higher ideals and greater cohesiveness to the student body of their college and felt that the YMCA might provide the best means for accomplishing this.

But, to establish a Y on campus, they first had to overcome various obstacles—chief of which was a requirement by the national organization that the local executive officers be members of a Protestant church. The students resolved this issue by deciding to de-emphasize religion and emphasize social service instead—which was acceptable to the National YMCA. Robert A. Millikan had already arrived on campus as part-time director of physical research and it is probable he influenced this decision.

Max Carson, a senior, was elected the Y's first president. He proceeded to outline the new organization's goals as he saw them: to create a student employment bureau and an organization to welcome new students on campus, and to seek a means for bringing the desired higher



Students attending Frosh Camp—which was established by the Caltech Y in the 1920s—play mountain golf at Camp Radford, located above Redlands, California. The photo is believed to be from the mid-1940s.

ideals and a religious influence—even if low key—into college life.

During the remainder of the academic year, the YMCA sponsored a regular weekly Bible class, made plans to welcome the next freshman class, started Max Carson's proposed student employment bureau, and began publication of a monthly newsletter. The officers also convened an assembly of the entire student body, during which they presented a short talk on the aims of the Y, listened to a mandolin solo, and joined in a recitation not only of the Lord's Prayer but also in several yells for the debate and basketball teams. Finally, they heard a report from the state YMCA secretary on the social service programs the YMCA was conducting in European prison camps.

Throughout the Y's first year, help came to them from the regional and

national YMCA organizations, and the state YMCA secretaries spent many hours on campus helping the Y develop its program and budget. The establishment of the employment bureau was particularly important. At that time, scholarships and student aid were virtually nonexistent and many students had to work long hours to meet expenses.

Today, the Caltech Y—which established a friendly separation from the YMCA in the 1970s when the Institute became coed—remains committed to providing educational, outdoor, community-service, cultural, and social activities for all Caltech students. To learn more visit caltechy.org.

“THE UNIVERSE HAS SPOKEN”

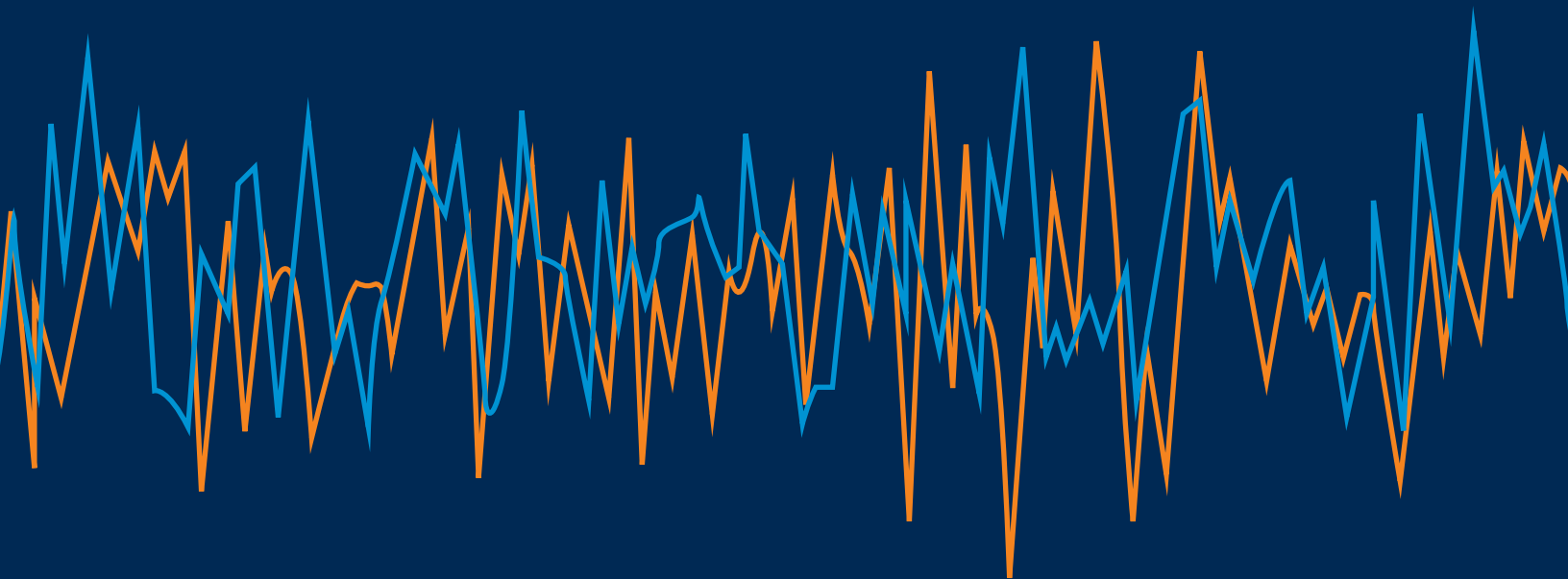
How the little-known field of numerical relativity helped teach scientists to read ripples in spacetime

By Kimm Fesenmaier

“Ladies and gentlemen, we have detected gravitational waves.” With those words at a press conference on February 11, 2016, in Washington, D.C., David Reitze, executive director of the Laser Interferometer Gravitational-wave Observatory confirmed rumors that had been circulating for months: LIGO had succeeded in detecting gravitational waves, ripples in the fabric of spacetime, here on Earth.

It was a huge moment for LIGO—and for science. The detection confirmed an important prediction of Albert Einstein’s 1915 general theory of relativity—namely, that massive bodies can curve space and time, and their acceleration or deceleration produces gravitational waves that propagate throughout the universe.

It was also a turning point for scientists who had been involved in another type of relativity: numerical relativity, a field in which physicists use supercomputers to solve



The plots on these pages show signals of gravitational waves detected by the twin LIGO observatories over a fraction of a second. The signals came from two merging black holes 1.3 billion light-years away. The LIGO data match the predictions very closely, and this diagram, above, compares data from both facilities, confirming the detection.

massive equations that are far too difficult for humans—and even regular computers—to solve, in part because they involve warped spacetime. The solutions allow relativists to simulate events like the binary black hole merger that produced the particular gravitational waves LIGO had detected in an attempt to figure out how the signals *should* look.

At the press conference during which LIGO researchers unveiled the details of the detection—that on September 14, 2015, a signal picked up, independently and about 7 milliseconds apart, at LIGO’s twin interferometers in Livingston, Louisiana, and Hanford, Washington—Caltech’s Kip Thorne, one of LIGO’s founders, described the event that produced the observed waves as a violent storm in the fabric of spacetime. “We have been able to deduce the full details of the storm,” he explained, “by comparing the gravitational waveforms

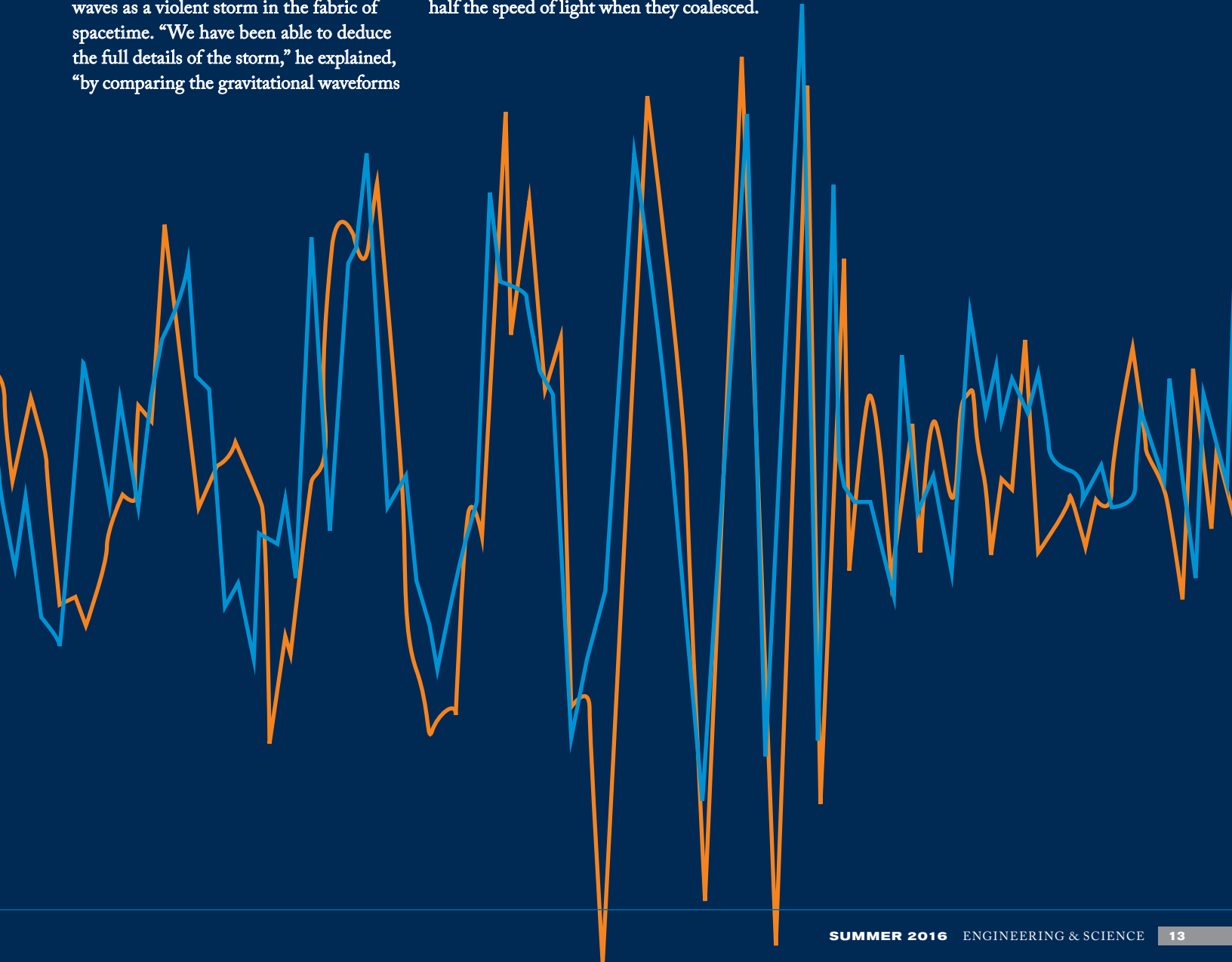
that LIGO saw with waveforms that are predicted by supercomputers.”

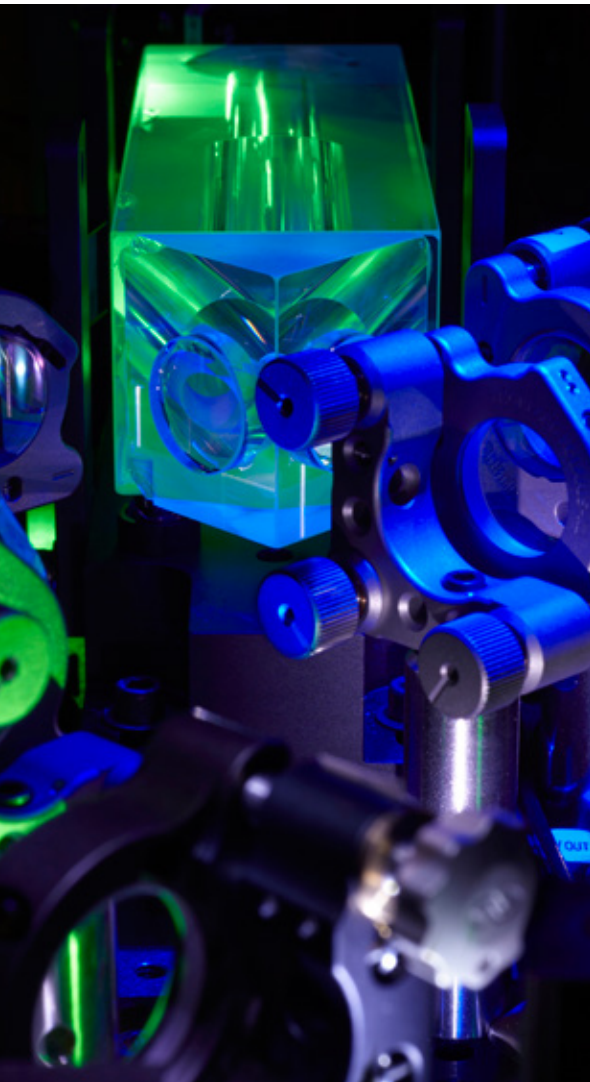
Those waveforms matched—with near-perfect precision—what the computers predicted from the merger of two black holes. Indeed, thanks to the numerical relativists and their simulations—and to the scientists who’d used those simulations to build approximate waveform models—the LIGO scientists were able to determine that one of the colliding black holes that produced their gravitational waves had a mass of 29 solar masses while the other had a mass of 36 solar masses. They were also able to deduce that the signal was from the final fractions of a second, 1.3 billion years ago, when the inspiraling black holes collided, and that they were traveling at nearly half the speed of light when they coalesced.

A BET AND A GOAD

That the numerical relativists would have been able to create a simulation with that much precise and detailed information was anything but clear just two decades earlier. In fact, it was an outcome that Kip Thorne was willing to bet against.

In 1995, Thorne was chairing an advisory committee to the Binary Black Hole Grand Challenge Alliance, a group formed by the National Science Foundation to encourage numerical relativists to try to simulate merging black holes. Thorne, a theoretical physicist, bet the Grand Challenge’s researchers that they would not be able to successfully model such a merger before LIGO had detected its first gravitational-wave signal.





Caltech's 40-meter prototype interferometer has been the testing ground for many theories and subsequent instruments and applications used at LIGO. Seen above are some high-stability mounts for super-polished mirrors and lenses for the prototype. The glass object is a fused silica optical ring resonator, which removes the angular jittering of the laser beam, smooths out the variations in power, and makes it possible for the laser to be used in the large interferometers.

“I was trying to goad them into working harder, being more effective,” says Thorne. In truth, he was quite invested in their success. Along with LIGO cofounders Rainer Weiss of MIT and Ronald Drever of Caltech—as well as many other collaborators—Thorne had labored through decades of theoretical work and instrument prototyping to finally witness the construction of the facilities that would house LIGO’s interferometers in Livingston and Hanford. But without simulations, recognizing a gravitational wave—if and when one zipped by—was going to be nearly impossible. The researchers would not only have little idea what such a wave should look like but they would be unable to distinguish a signal produced by a binary black hole merger from one produced by a neutron star and a black hole smashing together, or two neutron stars. And they certainly wouldn’t know how to look more deeply at and learn more about these individual gravitational-wave sources.

In other words, simulations—and the numerical relativists who produce them—were going to be key to the whole endeavor.

RELATIVE SUCCESSES

Thorne, Weiss, Drever, and others had been developing a vision for the kinds of science that gravitational-wave observation would enable since 1968. In addition, scientists had been working with prototype interferometers not only at Caltech but also at MIT and in Glasgow, Scotland, and Garching, Germany, for more than 15 years, trying to figure out how to build the mirrors, lasers, vacuum chambers, and isolation systems that would make the instrument capable of capturing these elusive waves.

LIGO is based on a fairly simple concept: the idea that laser light fired down two identical 4-kilometer “arms”—situated in an L shape—toward identical mirrors should bounce back to their point of origin at the exact same time. Any difference in

the two arrival times could be caused by gravitational waves compressing spacetime a tiny bit along one length while stretching it a similar amount along the other.

Although straightforward in outline, making this concept a reality has required pushing multiple technologies to new levels of performance for decades. After all, the “tiny bit” of change that those instruments are trying to detect is an alteration in distance of about 10^{-18} meter, or one-thousandth the diameter of a proton.

By the mid-1990s, it seemed possible that this seemingly impossible task might actually be doable in the near term. But in order to interpret the data, the scientists would need simulations of a kind rarely seen or accomplished before—a full solution of Einstein’s 10 field equations for the highly dynamical systems that are expected to produce gravitational waves. These solutions would need to include not just the gravitational waveform for the waves traveling in any direction but also the detailed, rapidly changing shape and size of the waves’ source and its curvature of spacetime at every point.

Of course, Einstein’s equations are not easy to solve. Each of these differential equations includes hundreds or even thousands of terms that must be solved for every moment in time and space. Just keeping track of all the numbers is a challenge, not to mention figuring out how to deal with the bizarre properties of black holes and strongly warped spacetime. And in the mid-1990s, attempts to solve these equations for black holes became unstable for reasons unknown at the time.

All of which is to say that, in 1995, the numerical relativists in the Binary Black Hole Grand Challenge Alliance had little confidence that they would win the bet with Thorne. Numerical relativists across the globe had been trying to run binary black hole simulations for decades, after all, and hadn’t even been able to compute

The LIGO findings were announced 100 years after Einstein first predicted gravitational waves.

The black holes that produced the gravitational waves detected by LIGO circled one another for millions of years before colliding.

The power emitted by the merging black holes was 50 times greater than the output of all the stars in the universe put together.



LIGO senior scientist Koji Arai explains the trends showing the variations in noise over a period of eight hours at Caltech's 40-meter prototype interferometer. The change from quiet to noisy in the bottom panel is due to ground motion caused by local Pasadena traffic. The lack of variation in the middle panel shows that the vibration isolation systems are doing their job.

a single black hole in full 3-D without the code crashing, much less a binary, says Mark Scheel, a research professor at Caltech who leads the numerical relativity efforts on campus.

"We were really worried," says Scheel, who, at the time of the bet, was a graduate student at Cornell. "We had no idea what we were doing wrong."

Eventually, Thorne became so concerned about the state of numerical relativity that he decided to form a group dedicated to it at Caltech. In 2001, he left the theory end of LIGO in the able hands of other physicists, and met with Saul Teukolsky (PhD '74), a former student of his who was running what Thorne regarded as the top numerical relativity group in the nation at Cornell University. ("Hooking yourself up with the best is a great way to get started," Thorne notes.)

Thorne and Teukolsky formed a collaboration—now called the Simulating eXtreme Spacetimes (SXS) project—which they later expanded to include partners at the University of Toronto, Cal State Fullerton, the Albert Einstein Institute in Germany, Oberlin College, and Washington State University. With seed funding from the chair of Caltech's Division of Physics, Mathematics and Astronomy at the time, Thomas Tombrello, and from then-provost Steven Koonin (BS '72), followed by funds from the National Science Foundation and crucial gifts from the Sherman Fairchild Foundation and Michael Scott (BS '65), the first CEO of Apple, Thorne established Caltech's numerical relativity group and invited Scheel and Lee Lindblom, a Caltech colleague in theoretical physics, to help lead it.

"LIGO and the numerical relativity

group were bets that Caltech made," says Thorne. "Caltech's willingness to invest resources in new science even when no one knows whether it is going to succeed is very impressive."

The new group hit the ground running. Within a few years, the Caltech numerical relativists and their collaborators had done a lot of work to help those in the field understand their common stumbling blocks, including the realization that the standard way of writing down Einstein's equations was not the right way to feed them into a computer. A reorganization of the equations into a new form enabled the computer to solve them without crashing.

Selecting the coordinates to use for whichever type of system they were simulating was also problematic. In some cases, what seemed to look like a gravitational wave in a simulation was in fact the coordinates themselves wiggling back and forth due to the oddities of warped spacetime; in others, two points labeled with different coordinates eventually came to represent the same point.

And then there were singularities. These are regions near the centers of black holes where spacetime has collapsed, creating an infinite amount of gravity and an infinite amount of curvature. Perhaps unsurprisingly, computers (as well as most human brains) don't deal well with infinities.

Then, in 2005, the field quite suddenly pushed past the bottleneck when physicist Frans Pretorius, then a postdoctoral scholar at Caltech, figured out a way of writing Einstein's equations so that unacceptable errors were kept in check. He also incorporated into his simulation the idea that since nothing can escape a black hole, it is OK to essentially cut out its interior—a method known as excision—thus eliminating the problem of singularities.

Using these and other techniques, Pretorius managed to simulate the merger

The waves measured were 1.3 billion years old.

The measurement was equivalent to measuring a signal the width of a human hair over the distance of more than three light-years.

More than 1,000 people have worked on the LIGO project.

of two black holes using a supercomputer, the first such simulation ever achieved. About six months later, groups at NASA's Goddard Spaceflight Center and at the University of Texas at Brownsville—using a completely different approach—produced another successful simulation of a binary merger.

And just like that, Thorne had lost his bet. He says he couldn't have been more pleased. "The bet was fun, and it was a way to focus the community's attention on some issues that I think are really important," he says.

READY FOR DETECTION

After those initial successes, the numerical relativists, struggling for an additional decade, gradually succeeded in simulating all sorts of black hole scenarios: identical black holes that did not spin, or that did spin, or that had different masses and the same or different spins; black holes whose spins caused space to whirl, dragging the plane of the holes' orbit into precession—which in turn caused the holes' spins themselves to precess, like rotating toy tops. The relativists also pushed upward the number of orbits they could follow. The longest published simulation, reported in 2015 by the SXS Collaboration, followed a black hole binary through 176 orbits, climaxing in a collision and merger.

These breakthroughs have given the LIGO scientists the simulations they need to be able to identify gravitational waves when they see—or hear—them, but the relativists' work is far from done, says Scheel. For one thing, he says, they need to figure out a way to seamlessly connect their simulations of the late epoch of a binary's evolution, when its bodies are orbiting close together, with analyses others have done of the earlier epoch when the bodies are farther apart—analyses that use an entirely different set of analytical tools.

Indeed, Scheel says, it's fortunate that the first LIGO event turned out to be a high-mass binary black hole system, for which LIGO's noise prevented it from seeing the earlier epoch. "That binary is something that we can simulate very well now," he notes. Currently the Caltech team is working on speeding up its computer code so the hundreds of simulations needed for

analyzing each LIGO event can be carried out quickly. The team also is developing a so-called surrogate model that will enable them to interface their simulations' numerical waveforms with the LIGO team's data analysis far more efficiently than is now possible.

When the LIGO team announced the first detection, it also essentially unveiled a new way to study the universe. These waves, after all, are capable of providing information about some of the most mysterious features of the cosmos, including black holes and the Big Bang. As Reitze said, "It's the first time the universe has spoken to us through gravitational waves. Up until now we've been deaf to gravitational waves, but today we are able to hear them."

Thorne emphasized that, even after 40 years of work, the announcement marked a beginning, not an end. "With this discovery, we humans are embarking on a marvelous new quest: the quest to explore the warped side of the universe," he said.

In the next 15 to 20 years, we humans will be helped along in that exploration by next-generation gravitational-wave windows on the universe: Advanced LIGO, which looks at gravitational waves that oscillate with periods of milliseconds, and three additional types of detectors that will be looking at gravitational waves that oscillate with longer periods. Just as the introduction of radio, infrared, and X-ray telescopes have each delivered surprises and new insights about the cosmos, scientists believe the new views provided by gravitational-wave detectors will fundamentally alter our understanding of the universe.

"The future of gravitational-wave astronomy is very bright and very long term," says Thorne, now the Richard P. Feynman Professor of Theoretical Physics, Emeritus. "I, personally, am looking forward to the day that, in large measure through gravitational-wave observation, we come to understand the birth of the universe. That, for me, is the biggest goal of this field . . . that, and discovering things that are totally unexpected." *ESS*

"LIGO is the most precise instrument on the face of the planet, and there are many more sources that it is going to detect. And it's going to get even better—more sensitive and more capable in the upcoming decades."

—*Fiona Harrison, the Benjamin M. Rosen Professor of Physics and holder of the Kent and Joyce Kresa Leadership Chair of the Division of Physics, Mathematics and Astronomy*

"The LIGO effort captures the essence of our dreams for Caltech—we want to be the place that takes risks when the scientific and technological payoffs can be large, and have the resolve and ingenuity to succeed."

—*President Thomas F. Rosenbaum, Sonja and William Davidow Presidential Chair and professor of physics*

LOOKING FORWARD INTO THE PAST

The Caltech community reflects on the importance and impact of the detection of gravitational waves and talks about what this breakthrough will mean for the future of astrophysics and beyond.

“Our knowledge of how the universe really works comes to us when we as a people make a **bold step** by measuring something about nature much better than ever before. The upgraded LIGO detectors have radically expanded our view of the universe. For the first time, humanity is able to receive signals from across the universe made entirely by gravity.”

—Rana Adhikari, professor of physics

“In the future, we expect to also be able to detect gravitational waves from the mergers of other compact objects, in particular, the mergers of binary neutron stars. These events release huge amounts of material, neutron-rich material, into interstellar space. This is likely the source of elements heavier than iron, like my wedding ring. Now my body is made up of carbon and oxygen and nitrogen—these are the elements that are forged in the core of stars and are now stardust from a supernova that exploded some 6 billion

years ago, leaving behind a dead neutron star and a lot of matter that formed our sun and planets, and us. But my ring, my ring probably came from two such dead stars merging together in a second death. I’m stardust. But my ring is neutron stardust. So we’re not just learning about extreme, exotic phenomena in our universe far removed from typical human experience. With these observations, we’ll also be learning about the origins of the stuff that we’re made of.”

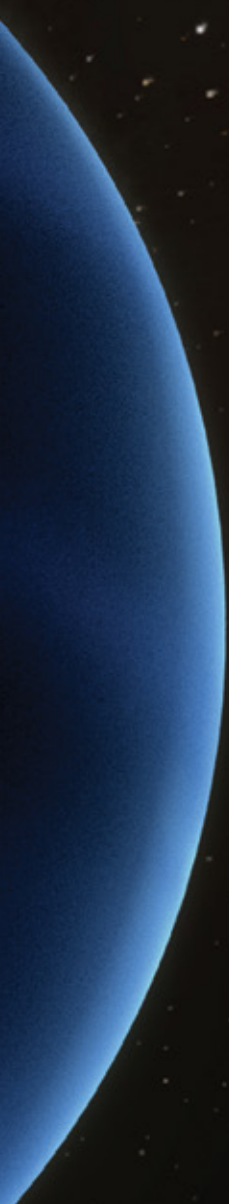
—Alan Weinstein, professor of physics

“When you have an abundant supply of neutrons, if some of them escape and begin to decay, or if some of them combine and form these very heavy elements like gold and platinum, and that subsequently decays, all of that can power a flash of light. Wouldn’t it be nice if in addition to finding the flash of light, we find it so fast that we can unravel all the astrochemistry as it happens? We have the opportunity to find it in these cosmic gold mines and cosmic platinum mines. Every single time that LIGO hears a gravitational wave, the telescopes in the Palomar Transient Factory completely robotically, completely autonomously, respond to this gravitational wave. So LIGO tells us that it happens somewhere in this big banana[-shaped area] in the sky, and this robotic telescope with a very, very wide-angle camera, within a few hours, will just image that entire area. If a few hours is too slow for you, then don’t worry. Because next we are building an even bigger camera on the [Samuel] Oschin 48-inch Telescope called the Zwicky Transient Facility. Then we can image this whole swath in just a few minutes. The challenge is very tough—we’re trying to find a needle in a haystack, and all we have is 24 hours. The good news is that at least eight times we’ve done this successfully, following up fast transients associated with Fermi gamma-ray bursts. Caltech is ready and the 21st-century gold rush has just begun.”

—Mansi Kasliwal, assistant professor of astronomy



**NINE
THINGS
TO KNOW
ABOUT
PLANET
NINE**



In January, Konstantin Batygin, assistant professor of planetary science, and Mike Brown, the Richard and Barbara Rosenberg Professor of Planetary Astronomy, announced that they had found evidence—through mathematical modeling and computer simulations—of a giant planet tracing a bizarre, highly elongated orbit in the outer solar system. This object, if found, would bring the total count of planets orbiting the sun back to nine, perhaps giving solace to those who were upset when Brown killed off Pluto a decade ago. From its mass to its orbit, here are some of the things Caltech astronomers are finding out about a potential Planet Nine.

1

Planet Nine has not yet been spotted, but its existence has been inferred from its gravitational effects on objects in the outer fringe of our solar system.

2

Planet Nine is estimated to be 10 times the mass of Earth, making it likely to look like a miniature version of Neptune.

3

Its inferred orbit is, on average, 20 times farther from the sun than that of Neptune.

4

The time it takes Planet Nine to orbit the sun just *once* is anywhere from 10,000 to 20,000 years.

5

Planet Nine gravitationally dominates a larger region of the solar system than any other known planet.

6

Brown and Batygin think that Planet Nine likely formed in the region of Uranus and Neptune, and got ejected to the outer edge of the solar system by a too-close encounter with Jupiter.

7

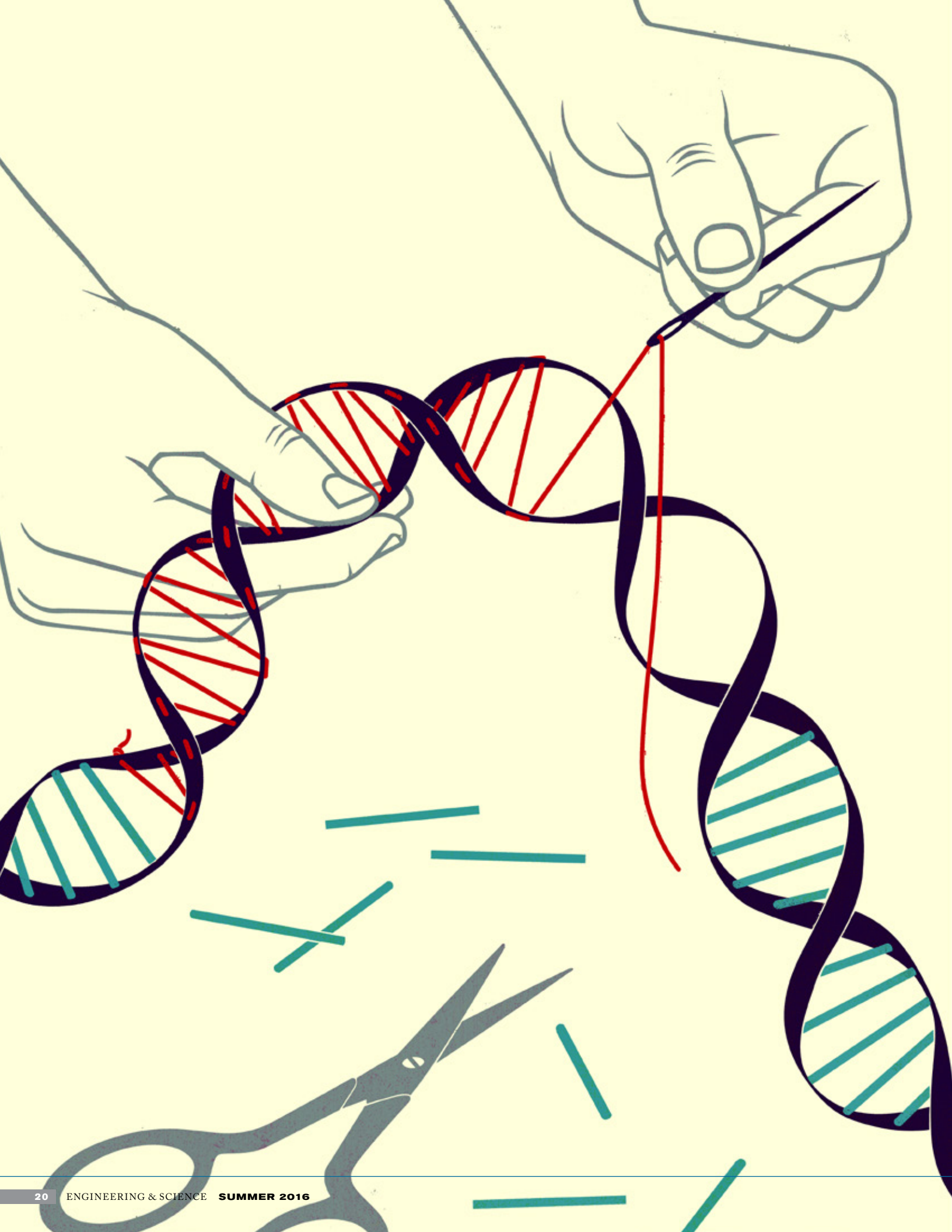
It's also possible, though, that Planet Nine is a captured rogue planet, meaning that it originated in a different planetary system, from which it was ejected, and got pulled into our solar system by the sun.

8

The Hubble Space Telescope should be able to see Planet Nine—if it can find it—though it would only be able to produce an image a few pixels across.

9

Astronomers worldwide have already begun searching their data for Planet Nine and proposing new searches to discover the object. Brown and Batygin are optimistic that Planet Nine will be found in fewer than five years.



THREADING THE NEEDLE

Biologist David Baltimore talks about the abundant promise and potential perils of the new gene-editing technique CRISPR-Cas9.

Late last year, a group of government officials, science policy experts, philosophers, and scientists—including Nobel Laureate David Baltimore, president emeritus and the Robert Andrews Millikan Professor of Biology at Caltech—convened at the National Academy of Sciences (NAS) in Washington, D.C., for the International Summit on Human Gene Editing. Several hundred people were there to discuss the scientific, medical, legal, and ethical implications of genome engineering technologies.

Such technologies—chief among them a now-widespread genetic tool known as CRISPR-Cas9, known colloquially as “DNA scissors”—allow scientists to make precise edits to the genome, or the entire genetic script, of an organism. By essentially rewriting genomes, researchers can, in weeks rather than years, create animal strains that mimic human diseases to test new therapies, easily knock out genes in the cells of animals and humans to test their function, and even change DNA sequences to correct genetic defects. Such edits can be made in both body cells and in germ-line cells (sperm and eggs), thus allowing scientists to alter heritable genes.

“Over the years, the unthinkable has become conceivable,” said Baltimore at the December 2015 meeting, which was sponsored by U.S., U.K., and Chinese scientific societies. “We’re on the cusp of a new era in human history.”

We spoke with Baltimore—who led the organizing committee of the summit—about these new technologies and the issues they raise.

What was your motivation for participating in the conversation about the uses of genome engineering technologies?

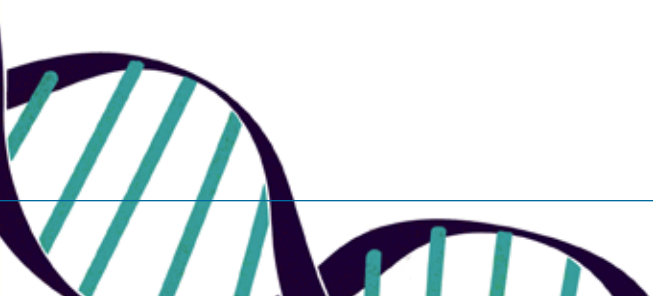
I was most concerned about the ability to carry out germ-line modifications of humans using this technology. Other issues came up that seemed to me less concerning at the moment, like guidelines for basic research or for somatic gene therapy, which is the alteration of cells whose genomes are not passed along to the next generation, as opposed to heritable gene therapy.

What is the big issue with human germ-line modification?

The big issue is how simple it is, at least conceptually, to modify cells—embryonic stem cells as well as somatic cells. The major concern is the potential for off-target effects: If you carry out the germ-line modification of a gene that you have identified as of concern, how do you know that, somewhere else in the genome, there hasn’t been an alteration that you didn’t plan to do but that has occurred anyway? Most of the genome is not

coding—it doesn’t code for anything. So you wouldn’t necessarily see a protein change. But that change would be heritable for generations into the future, where it might cause problems. You want to be pretty sure that such off-target alterations are not happening.

We know that people have put a lot of effort into minimizing such off-target effects. Whether they have been minimized enough is a very important safety consideration.



Are there problems beyond off-target effects that could occur if safety and ethical guidelines are not followed? If so, what are the most dangerous risks?

We did not specify what the risks might be because that involved thinking about too many specific events. As a class, alterations of heritable traits for “cosmetic” purposes represent a type of genome modification that poses serious concerns because we may not know how the altered genes will interact with the rest of the genes in the body and with the genes of the offspring of the original carrier of the alteration.

seems to me to be an unalloyed good. Therefore, the question becomes, do you need to use genome alteration technology to accomplish that end or is there some other way to accomplish that?

But there are situations that are not that clear-cut . . .

Exactly. You go from, on one side, Huntington’s disease, and on the other side, the desire for a more intelligent child. One is easy—it can be fixed by changing a single gene. The other is much more complicated, since intelligence certainly isn’t determined by a single gene. It is multigenic—the result of many genes. One is a pretty straightforward medical decision; the

How do we manage that?

My personal thought is that the best we can do is to make absolutely unambiguous the consensus feeling of society. Because the scientific community is an international community, we do have the ability to at least provide moral guidelines.

Any kind of modification that involves something as elusive as intelligence is a long way off. We don’t understand it well enough to make modifications today, and so, to an extent, we are trying to establish a framework that will serve the world well into the future. That is a big order, and whether an international meeting can grapple with anything as profound as that, we will see.

My personal thought is that the best we can do is to make absolutely unambiguous the consensus feeling of society.

Are you and your colleagues concerned about the potential for using this technology to create “designer” babies?

I think the thing to do is to distinguish between the long-term concern about modifications that are heritable but made for reasons that are “cosmetic,” and a situation in which a modification is made in order to ameliorate a serious human disease.

The example that I find most compelling is Huntington’s disease. It involves a mutation in the genome that most people don’t carry; the few people who do carry it suffer very serious deleterious consequences that only become apparent with age. Ridding the genome of that modified gene

other is an issue that is very culturally bound. So those are the two poles, and then there is everything in between.

For the in-between situations, that is just a judgment call?

Yes, it is a judgment call.

Who makes the decisions in those cases?

Society, in the end, will make those decisions. The problem that I think everybody has with it is that although society has the ability to make decisions like that, it is a big world. And you could imagine things being done in other jurisdictions where we don’t have control.

What do you see as some of the most exciting applications for technologies like CRISPR-Cas9 that would have a positive impact on human health?

I think that the most exciting applications are in the research laboratory, where models of disease can be created and manipulated. Later, I hope that we will perfect methods for ridding the human genome of single-gene defects, like the ones that cause Huntington’s disease. Gene editing is not the only way to prevent transmission of such defects to progeny, but it could become the easiest and most certain way.

You and the rest of the organizing committee released a statement at the end of the summit that offered some guidelines for the scientific community. What were the key conclusions about how to move forward with technologies like CRISPR-Cas9?

The key conclusions were that we should not go ahead with germ-line alterations until we are confident of the safety of the alteration procedure and there is a widespread consensus that the alteration will improve human

health without a significant likelihood of an unexpected deleterious outcome. To me that means when we are confident of the technology, we will want to start by returning mutant genes to their wild-type—or naturally occurring—configuration. But a lot of decisions and recommendations will need to be made along the way in order to do safe and ethical basic research that could lead to confidence in the technology. So we also called for an ongoing international forum to encourage coordinated conversations and policy making among a wide range of experts.

Forty years ago, you were one of the organizers of the influential Asilomar Conference on Recombinant DNA, which laid out voluntary guidelines for the use of genetic engineering—the same type of guidelines you and your colleagues are advocating for now with genome engineering. What was the original inspiration for convening the Asilomar Conference?

It was the advent of recombinant DNA technology that drew our attention. We all worked in the biological sciences. We recognized that recombinant DNA technology was a game changer because it was going to allow scientific investigation of questions that heretofore had been unavailable. In some ways, many of us had designed our careers around the inability to do this kind of work, and, suddenly, we were going to be able to do things that we had only previously dreamed about, if we had considered them at all.

But at the same time, there seemed to be potentially problematic aspects to it, in particular the ability to modify organisms, mainly microbial organisms, in ways that could have given the organisms the ability to be a danger to human health.

Actually, we simply did not know

whether that was a realistic concern or not. As we talked to other people, we discovered that no one knew. So it seemed like a good idea to take a breather and to give consideration to these concerns of potential hazards in an international meeting that would be convened in the United States.

Was there some thought that if you tried to self-regulate you could avoid governmental regulation?

It wasn't a matter of avoiding governmental regulation. It was that we thought that we—the scientific community—were uniquely capable of putting in perspective these new capabilities. The answer might have been to have legislation. In fact, as our thinking progressed, we realized that the very best situation would be to avoid legislation because legislation is very hard to undo. We wanted to be sure we would have the flexibility to respond to inevitably changing scientific perspectives.

In retrospect, do you think Asilomar was a success?

It worked out very close to how we hoped it would. That is, as we learned more, we became more comfortable with the technology; as we investigated potential hazards, we saw less and less reason to be concerned; and we had a built-in flexibility in the system to allow it to evolve in the context of newer understanding.

Are you aware of any situations where scientists did not follow the rules?

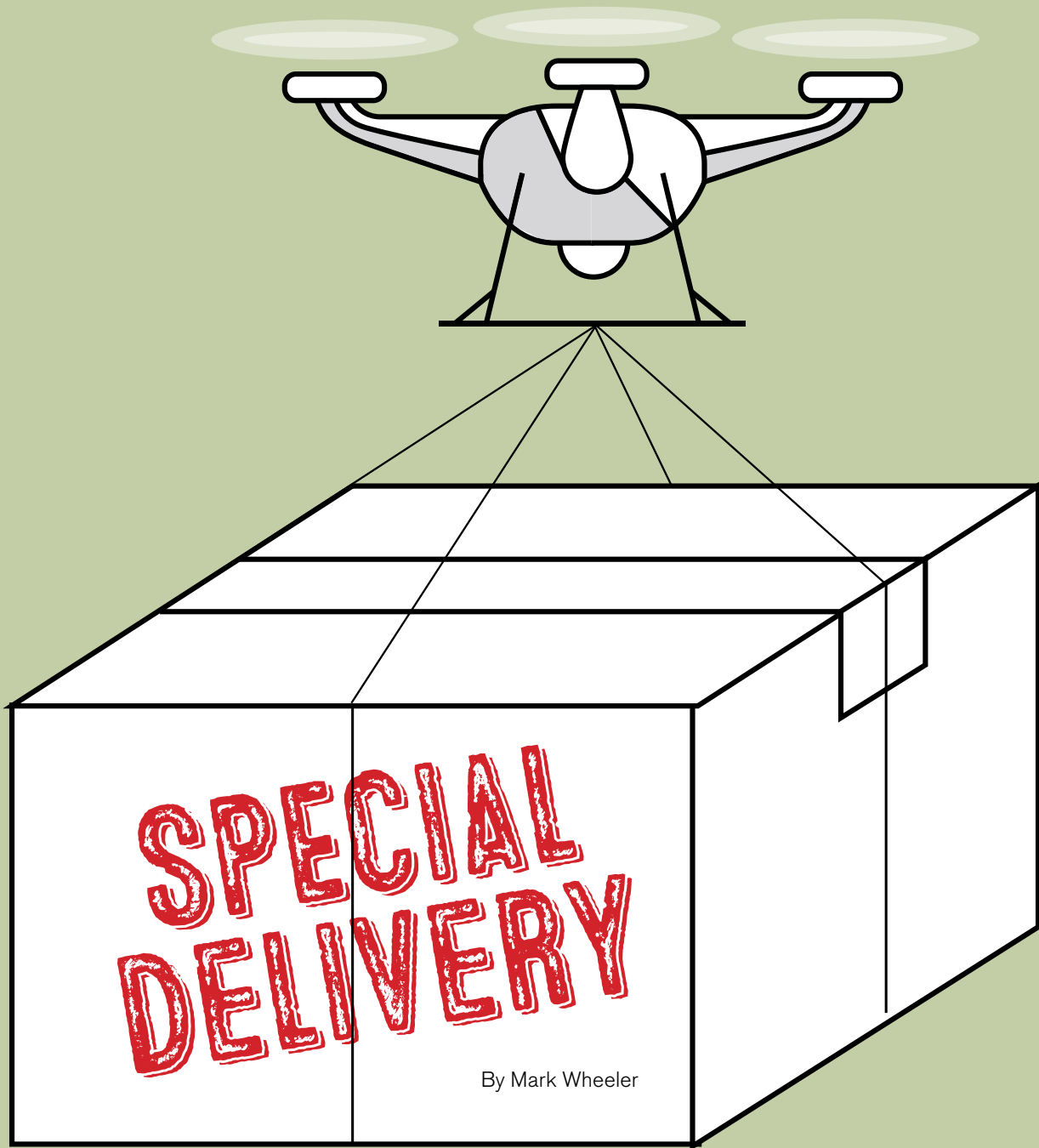
To my knowledge, that has never happened.

Where do you see this technology in 10 years? 100 years?

That is a good distinction—10 years versus 100 years. The latter is very hard to think about, because we have really

no idea what scientific advances are going to be made in the next 100 years. About all we can be sure of is that they will be impressive and maybe revolutionary, and will present us with a very different technological landscape in which these questions will evolve. In 10 years, we certainly are likely to know the outline of what we are likely to see, and it is not going to be a whole lot different from what we are seeing today. I would guess that in 10 years, we would understand multigenic traits better than we do now. I do suspect that people will be gratified that at this time we began the basic considerations, because the problems will get more difficult rather than easier. [eSS](#)







From the exploration of other planets to the meanderings of single cells through our bloodstream and into our tissues, Caltech researchers are thinking about transportation in unexpected ways. They're using transformative delivery methods to land on Mars, collect data in hard-to-reach locales, and shepherd drugs to the brain, and they're doing so in order to better be able to ask big questions about the origins of life, to monitor the earth's emissions and overall health, and even to treat some of the most devastating diseases we encounter.

Dispensing Drugs

Chemical engineer Mark Davis didn't start his scientific journey looking for new ways to treat cancer. But it's where his research has taken him in the years since his wife, Mary, was diagnosed with the disease in 1995. She beat it, but only after a long stay in intensive care as a result of the side effects of her chemotherapy. So she turned to her husband and, in essence, said "make this better."

At first he was taken aback—after all, Davis is an expert in designing catalytic materials that speed up chemical reactions, not drugs that can attack some of the most deadly and difficult-to-treat diseases. But then he did what any self-respecting scientist would do: research.

Davis realized that a major part of the solution for fewer side effects from chemotherapy lies in the ability to set the drugs on a particular path to the tumor. "If you can keep cancer drugs away from healthy tissue, the awful side effects that are typically manifested would go away," he says. The problem is, most cancer drugs are like pharmaceutical carpet bombs. Because the molecules comprising these drugs are so tiny, they can squeeze their way through the wall

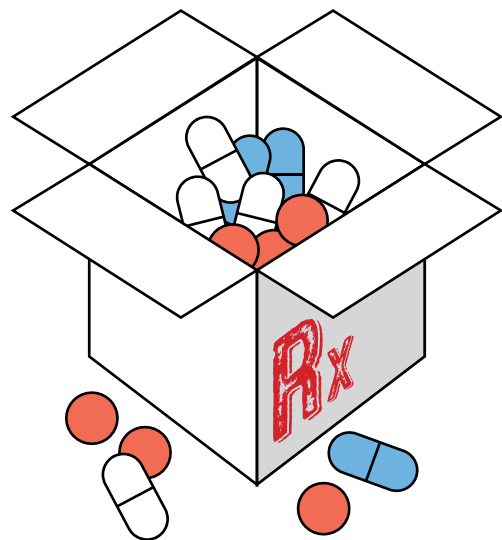
of a blood vessel and wend their way to healthy tissues where they penetrate and destroy cells.

"They go into bone marrow and kill cells that make up your immune system, into hair follicles and make your hair fall out, and into other organs, causing failure," says Davis.

Building on his experience with nanomaterials as a result of his catalysis work, he came up with the idea of building a nanoparticle delivery vehicle that would encapsulate the therapeutics and carry them to where they were supposed to go. While small in size, the nanoparticles are bigger than the chemotherapy molecules they are ferrying and also too big to slip out of the bloodstream into healthy tissue. In theory, Davis designed nanoparticles that should stay in the blood until they reach a tumor and then release their payload in the tumor—thus allowing the drugs to destroy solid tumors, like those of lung and breast cancer, while sparing healthy tissue.

Over time, he and his colleagues settled on nanoparticles made of cyclodextrins, which are a form of sugar. "Cyclodextrins are very biocompatible molecules, with a low toxicity," Davis says. "So, in humans, they sneak past the immune system." They soon recognized that 50 nanometers was the sweet spot for size, since the nanoparticles were then big enough to carry many cancer drug molecules yet small enough to travel in the blood and penetrate a tumor.

Davis's first success was with mice and used a cyclodextrin nanoparticle carrying a well-known chemotherapy drug, camptothecin. Davis and his collaborators tested the drug on various cancers—pancreatic, lung, breast, and more—and found that their delivery vehicle did indeed deliver. Because tumors are always growing new blood vessels, they give the nanoparticle access to the tumor



through blood. Once the nanoparticles are inside, chemical sensors within the nanoparticles control the release rate of the delivered payload. By design, the remnants of the disassembled nanoparticle are then flushed harmlessly out of the body in the urine.

Davis's nanotherapy—developed and tested primarily by Cerulean Pharma Inc., a company that Davis is a consultant for and holds stock in—has now been used in over 10 clinical trials, many of which have been

Phase II trials that test for both safety and indications of efficacy. Data from ongoing trials will be used later this year to assess whether the nanoparticle will enter Phase III trials that can be used to enable FDA approval.

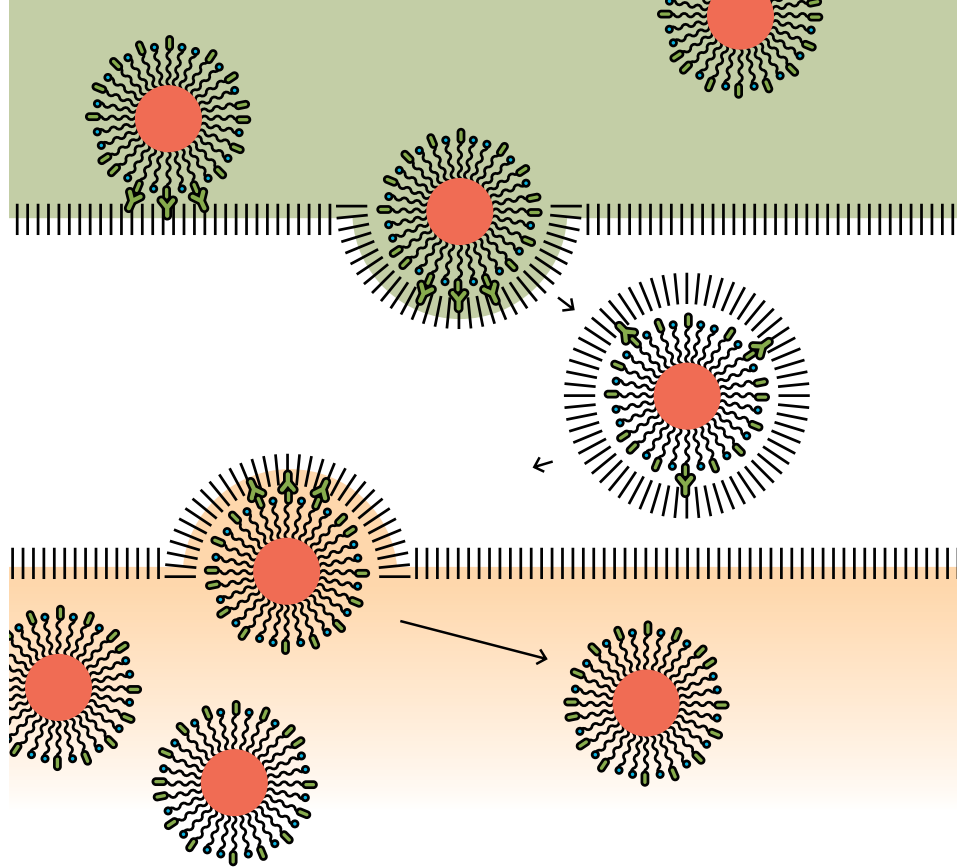
“So far the side effects in all these trials have been very low,” Davis says.

In March 2016, Davis and his coworkers reported in the *Proceedings of the National Academy of Sciences* on a nanoparticle clinical trial, where the nanoparticles were given intravenously to patients with stomach cancer. Biopsies showed evidence that the nanoparticle delivered its drug only to the tumors in the nine patients treated, and not in their adjacent healthy tissue.

“Right now, if a doctor wants to use multiple drugs to treat a cancer, they often can’t do it because the cumulative toxic effects of the drugs would not be tolerated by the patient,” Davis says. “With targeted nanoparticles, you have far fewer side effects, so it is anticipated that a drug combination can be selected based on biology and medicine rather than the limitations of the drugs.”

Next he hopes to surmount one of the biggest challenges in creating new therapeutics—penetrating the blood-brain barrier (BBB) for delivery of drugs to the brain. The BBB is a cellular barrier that controls the entrance and exit of molecules into the brain, e.g., it lets nutrients in but efficiently keeps foreign substances out, including most therapeutic drugs. “This is a huge goal,” says Davis, “not only for treating brain cancers and other diseases of the brain like Parkinson’s and Alzheimer’s diseases, but also because many cancers that start in the liver or breast or elsewhere in the body can metastasize to the brain and become the cause of death.”

Last year, Davis and his coworkers reported in the *Proceedings of the National Academy of Sciences* a big



Chemical engineer Mark Davis has been able to send experimental nanoparticles through the blood (green layer), transporting them across the blood-brain barrier (white) and into the brain (orange layer) using a mechanism called transcytosis. Next, he will try to pair the nanoparticles with a chemotherapeutic. If successful, it would represent an important breakthrough for treating brain cancers.

step toward this goal by borrowing from biology to successfully send 80-nanometer particles across the BBB in a mouse study using a mechanism called transcytosis. Transcytosis is the process by which various macromolecules, including proteins, are transported from the blood, across the cells that make up the BBB, and into the brain. In Davis’s study, nanoparticles containing an iron-binding protein (called transferrin), which naturally crosses the BBB to bring iron into the brain, hijacked the transcytosis process to get past the BBB and into the brain.

The next step, Davis says, is to pack a nanoparticle with both the transferrin protein and a therapeutic; if that, too, can be shown to deliver as expected, he would want to eventually move the technique on to human clinical trials.

While those are Grand Canyon-

esque goals, Davis thinks the use of nanotherapeutics will someday become commonplace. They could well become a primary delivery system for personalized medicine, he says. “In the ultimate manifestation of the concept, one could envision even prophylactic treatments. For example, you have a family history of a certain disease or you have an X or Y gene that makes you susceptible to something bad. Your doctor will take a finger prick of blood, and you will be given a personalized nanoparticle containing the right drug that will circulate throughout your body, preventing the disorder from ever gaining a foothold. It would have few if any side effects, bypass healthy tissue, and you wouldn’t even think about it. It will be like taking an aspirin.”

Collecting Information

Engineer Mory Gharib is focused on finding a better way to get a very

different kind of job done. Instead of transporting drugs throughout the body, his focus is on figuring out the best ways to take the already nearly ubiquitous autonomous drones and turn them from playthings into a workforce that can do the boring, expensive, and/or dangerous jobs that humans shouldn't be doing, like 24/7 monitoring of pipelines and rapidly delivering alerts of potential leaks; traveling to the way-distant shores of space to collect information; and entering collapsed buildings or damaged nuclear power plants and reporting back on conditions inside.

"The majority of drones and robots out there now are still toys," says Gharib (PhD '83), the Hans W. Liepmann Professor of Aeronautics and Bioinspired Engineering and vice provost. "There's nothing wrong with that, but we are now at the cusp where autonomous drones can have a meaningful impact on humans. The opportunities for drones to enhance science and our lives are numerous."

Gharib anticipates drones that will do the heavy lifting on construction sites, for example, or monitor farmland to detect a threat from insects and then do localized spraying with the minimum amount of pesticide needed. He believes they will also improve the delivery of everyday goods while reducing the carbon footprint.

He notes, however, that there are fundamental challenges that must be overcome to allow this technology to reach its full potential. That's why this spring Caltech established—with the help of a generous gift from investor and philanthropist Foster Stanback and his wife, Coco—the Center for Autonomous Systems and Technologies (CAST). Directed by Gharib, the center is poised to attack the multifaceted challenges of autonomous systems by taking advantage of the expertise that cuts

across Caltech's divisions and JPL.

Among the baker's dozen of scientists affiliated with CAST, Beverley McKeon, professor of aeronautics and assistant director of the Graduate Aerospace Laboratories, builds small-scale models of aircraft to study turbulent flow. This is not just to help passengers avoid nausea when their airplane hits an unruly pocket of air but also to design more streamlined drones and thus avoid them being knocked off course when strong winds are blowing.

Richard Murray, the Thomas E. and Doris Everhart Professor of Control and Dynamical Systems and Bioengineering, recognizes that drones and robots have the potential to exceed the capabilities of humans, but—like humans—they will have to be able to adjust to their environment in real time and also be able to self-correct. So Murray and his research group are exploring decision-making, resource allocation, and fault handling in unmanned, autonomous vehicles and mission systems.

Pietro Perona, the Allen E. Puckett Professor of Electrical Engineering, teaches machines how to "see" like humans do. A drone that can not only capture and deliver images but also understand what those images show would be useful to scientists and to itself. Perona is mainly interested in the study of visual categorization of scenes, objects, and behavior a vehicle navigating in complex environments may encounter. For example, an unmanned rescue vehicle in an earthquake-stricken city has to be able to recognize and classify other vehicles, people, signals, equipment, etc. It also has to be able to judge the actions and intentions of humans and animals.

Gharib's own interest in the field is in applying his expertise in small-scale fluid flow and bioinspired fluid dynamics to help design more effective

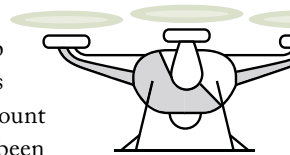
and versatile drones. What has held back the final advance of the necessary software, he says, is a common barrier: money and commercial interest. But that is starting to change, as the work of Lance E. Christensen shows.

A 2003 Caltech doctoral graduate in physical chemistry, Christensen is now a senior atmospheric scientist at JPL. He doesn't build drones; instead, he uses them to carry his instrumentation to go out and, as he says, "sniff stuff." He invents tunable laser spectrometers that indeed basically sniff the atmosphere for trace measurements of gases. Such spectrometers measure the abundance of atmospheric gases such as methane, water vapor, and carbon dioxide.

Christensen was part of the team that developed the Tunable Laser Spectrometer (TLS) for the Sample Analysis at Mars (SAM) suite of instruments on the Mars Science Laboratory (MSL) Curiosity rover. TLS investigates the composition of the planet's atmosphere and compounds extracted from the surface of Mars. These days, Christensen's work has expanded to include collaboration with private industry; he is partnering with the Pipeline Research Council International (PRCI) and Pacific Gas & Electric (PG&E), a gas and electric utility in Northern California.

"There is a natural relationship between industry and science," says Christensen. "For example, the amount of methane in our atmosphere has been growing now for the last decade after a five-year pause. Why don't we know where it's coming from? How can we not know our Earth's systems? Is it all these leaky pipes? Is it fracking? These questions cross over with industry."

As the inventor of the Open Path Laser Spectrometer (OPLS), which can measure small natural gas leaks (< 1 standard cubic foot per hour) hundreds of meters downwind, Christensen



adapted the instrument for industry to act as safety equipment and, when placed aboard drones, to look for leaks along thousands of miles of natural gas pipelines.

When Christensen was first starting out, he placed his data-collecting instruments on high-altitude balloons; later, he moved on to NASA aircraft for science campaigns such as the Mid-latitude Airborne Cirrus Properties Experiment. Today, he places his instruments on a quadcopter drone that he can hold in his hand; in February, along with colleagues from UC Merced and PRCI, he flight tested the OPLS in order to see how far downwind and how high he could detect methane leaking out of the ground.

“The quadcopter is stable, it doesn’t crash, and it doesn’t get tired,” he says, adding that he’d like to integrate an electrical landing pad into the system. “When a drone runs low on power, it would land on the pad to recharge while another drone lifts off to take its place.”

It’s an ideal solution for industry, particularly those companies that are responsible for working with or maintaining the nation’s aging energy infrastructure. In PG&E’s case, drones would be a much easier and cost-effective way to monitor pipelines like those in the Bay Area’s hilly regions.

One last hurdle to widespread use of drones, says Christensen, is the government’s concerns around privacy issues and the safety of other aircraft. For those reasons, the Federal Aviation Administration is moving cautiously on developing regulations for their use.

Christensen understands the agency’s slow pace. “People have mixed feelings about drones,” he says. “And with the rise of miniaturization and the growing capability of this technology, it gives a lot of us pause for thought, sometimes keeping us up at night.

“But if people can get rid get rid of their preconceived notions of drones, their utility could be endless,” says Christensen. “Think about having tiny drones floating just above the tree line, monitoring leaks from transmission lines. That’s something humans will never be able to do. The public might go for that.”

Transporting Tools

Geochemist Ken Farley doesn’t have to worry about public approval. He’s the project scientist for Mars 2020, the new rover mission, which—if the popularity of the Curiosity rover is any indication—will draw the excited and curious eyes of citizens around the globe.

But what Farley *does* have to worry about is the mission’s overall scientific success. He also has the obligation to meet the “very hard” launch date of 2020—when Mars and Earth are closest in orbit to each other. And he’s the guy who must help define the science goals for the mission and determine how to pack an assembly of all-new scientific instruments onto an existing rover.

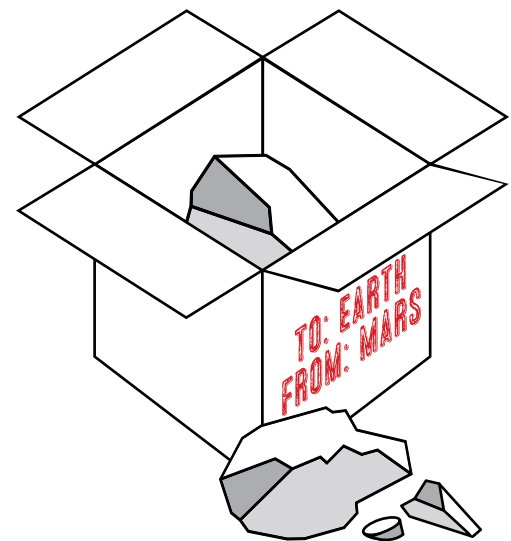
That rover will be a souped-up version of Curiosity, which still putters along to this day. That’s good, says Farley, in that the scientists know they have a proven and reliable platform. “The fundamental design is in place,” he says “but our challenge is that there’s a whole assembly of new instruments we have to cram onboard.”

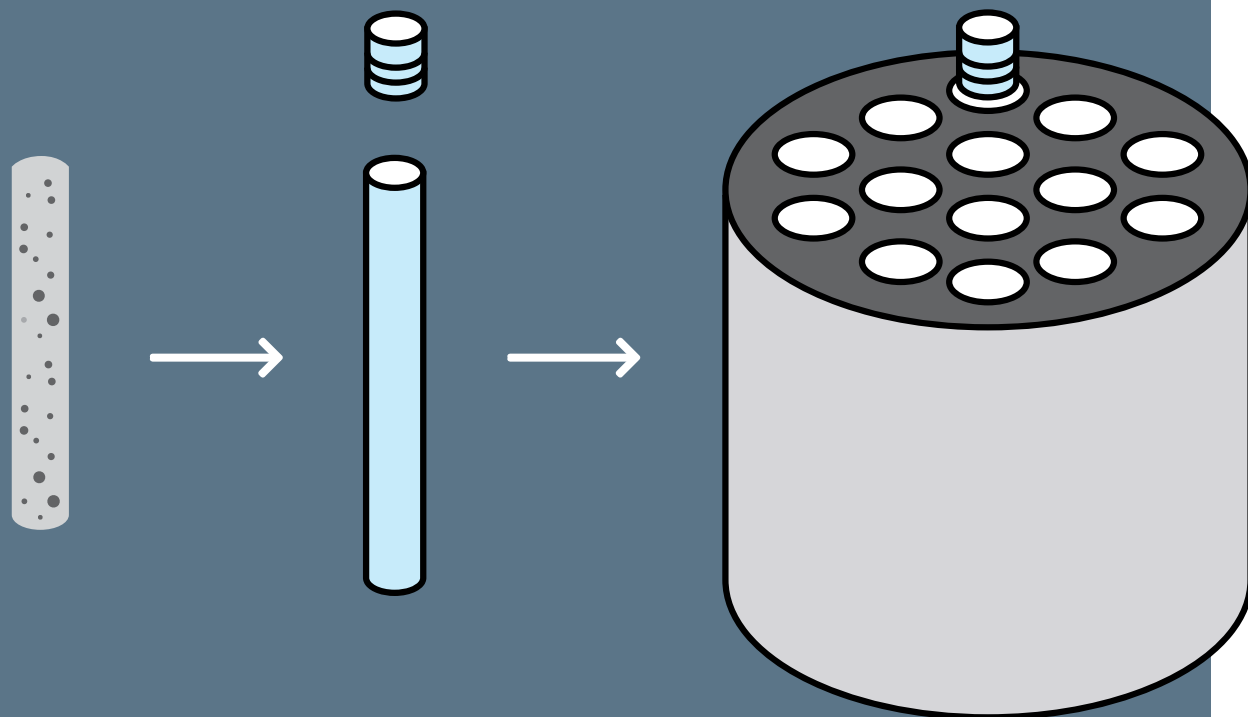
The overarching mission of the 2020 rover, per NASA, is to “seek the signs of life.” Specifically, it has four main objectives, one of which is to prepare the way for human exploration of Mars. To that end, the rover will include a weather station to help scientists better understand the martian atmosphere and an in situ resource utilization (ISRU) instrument, which will be tested for

its ability to convert atmospheric carbon dioxide into oxygen, both for future human consumption and for future propellant.

Each Mars mission builds on previous successes and, like the MSL, which launched in 2011, the 2020 rover will perform an extensive exploration of its landing site to understand the geological processes that helped form the surface of the planet. While the Curiosity rover is seeking (and finding!) evidence of habitable conditions, the 2020 mission will seek actual biosignatures—physical structures or molecules that show evidence of past or present life—in the rocks on Mars.

The subject of whether or not there was once life on Mars is certainly a fascinating one, but Farley believes that important questions will arise even if that search fails. “If we bring all the tools to bear on such an environment and *don’t* find signs of life, what does that mean?” he says. “If that’s the case, what, then, was the ‘spark’ that jump-started life on *our* planet?” He notes that some researchers now believe





This illustration shows a prototype for hardware to cache samples of cores (left) drilled from martian rocks for possible future return to Earth. A major objective for NASA's Mars 2020 rover, as described by Caltech's Ken Farley, would be to collect and package a carefully selected set of up to 35 samples in a cache that could be returned to Earth by a later mission.

life as we know it on Earth actually originated on Mars.

The biggest challenge of the mission, however, is likely to be the collection and preparation of returnable geologic samples for possible delivery back to Earth by a future mission. The word “returnable,” Farley says, has a technical definition—the cache has to meet a series of criteria, and one is that it has to have enough scientific merit to be worth the expense of bringing it back.

“There is some number of samples, probably between 20 and 35, that would make that worth doing,” says Farley. “If it’s less than that, it may not be worth bringing back. So, in some sense, we have a gun to our heads to collect a large number of samples.”

That said, Farley is prepared to be patient. “We’ve learned from Curiosity that everything takes a long time,” he explains. “Driving and drilling takes a long time. That’s motivated a lot of the discussion of landing sites. You’ve got

to have targets you wish to drill that are close together, and they can’t be a long drive from where you land. But there also has to be diversity because you don’t want 15 copies of the same sample.”

Plus, the Mars 2020 rover has a “warranty” of roughly only a couple of years, Farley says, so it’s critical for the rover to be able to collect its samples in that time. He yearns for the speedy rover used by Matt Damon in the movie *The Martian*.

“I wish,” he laughs. “We tell the rover to go here, it moves 50 meters, very slowly. Autonomy, and autonomous driving, is a challenge.”

In 2017, Farley and the other mission scientists will decide exactly where the rover will land. He notes that the proposed sites break roughly into two environments: crater lakes with deltas and hydrothermal sites. “They are the most likely to have ancient life in them and to have preserved the evidence of it,” he notes.

“But even if we don’t find signs

of life on Mars, we are likely to bring back rock samples that will have the prebiotic soup,” says Farley. “From those we’ll be able to ask: What were the chemical building blocks? It’s the question of the origin of life, and I find that very exciting.” *eS*

Mark Davis is the Warren and Katharine Schlinger Professor of Chemical Engineering. His work on nanoparticles is funded by the National Cancer Institute.

Mory Gharib is the Hans W. Liepmann Professor of Aeronautics and Bioinspired Engineering, director of Caltech’s Graduate Aerospace Laboratories, and vice provost.

Lance E. Christensen is a senior atmospheric scientist at JPL. His work is supported by the Pipeline Research Council International.

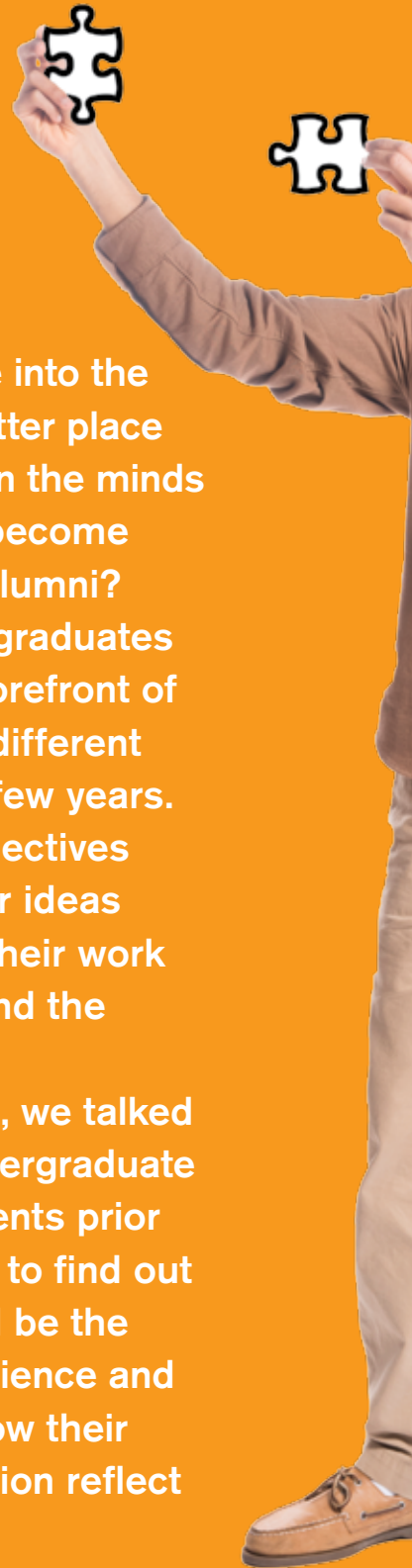
Ken Farley is the W. M. Keck Foundation Professor of Geochemistry. The Mars 2020 mission is funded by NASA.

The Next BIG Thing

By Nehaly Shah

To get a glimpse into the future, what better place is there to look than the minds of those about to become Caltech's newest alumni? After all, our 2016 graduates have been at the forefront of research in vastly different fields for the past few years. Their unique perspectives have informed their ideas of the future, and their work will reach far beyond the confines of a lab.

With that in mind, we talked to a handful of undergraduate and graduate students prior to commencement to find out what they think will be the next big thing in science and engineering and how their plans after graduation reflect those ideas.





I believe that the future of science, technology, engineering, and mathematics (STEM) will place a greater emphasis on implementation and impact of research. While rapid economic growth and globalization have introduced numerous difficult challenges, society has acquired powerful new tools and technology to develop and implement solutions for these issues.

I will be working as a management consultant after graduating to expose myself to business and strategy. That way, I can perhaps one day help new discoveries and ideas produce a tangible impact on people's lives."

Aditya Bhagavathi
BS in Computer Science

I believe the future of planetary and space exploration will follow two paths—one, the search for life beyond Earth within the solar system, and two, the characterization of exoplanets.

For the solar system, the initial survey of its major worlds was just completed with the New Horizons flyby of Pluto, and therefore a new focus will likely emerge. That initial survey has revealed several worlds to be potentially habitable, including Mars, Europa, and Enceladus, with the former two already targets for future missions. These new missions will not only reveal more about these worlds but also force us to reevaluate what life is, how it arises, and how it endures.

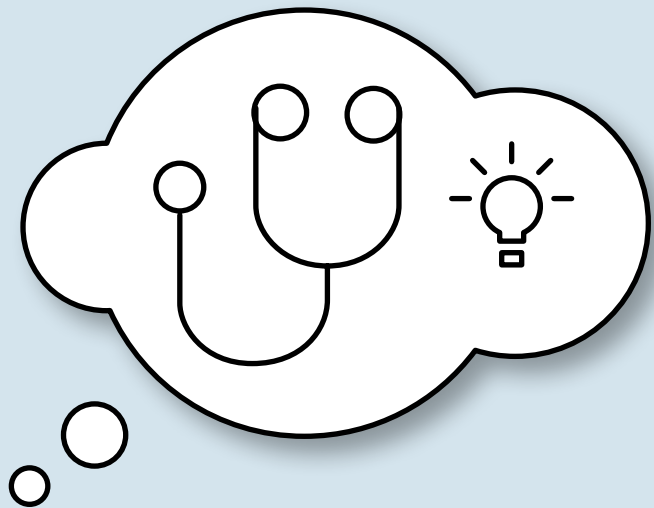
For exoplanets, the diversity of worlds is immense. From giant planets that orbit their host stars in less than a day to habitable planets with permanent daysides and nightsides, exoplanets offer a tremendous opportunity to understand the planets in our own solar system. With the rapid development of technologies, instruments, and observing techniques, the flood of data regarding exoplanets will only continue. I plan to be among the scientists who will analyze this data and combine their results with theoretical models to investigate what these distant worlds are like. By doing this, we will be exploring our place in the universe and whether we are alone within it."

Peter Gao
PhD in Planetary Science

When asked what he would do with his degree in philosophy during a routine dentist appointment, David Silbersweig, MD at Brigham and Women's Hospital and Academic Dean at Harvard Medical School, responded with a single word that spoke volumes: 'Think.' Simply put, I too want to think. I want to learn how to think at a complex level such that my ability to think and subsequently solve problems allows me to change lives. The history and philosophy of science degree at Caltech has given me exactly this. According to Silbersweig, 'If you can get through a one-sentence paragraph of Kant, holding all of its ideas and clauses in juxtaposition in your mind, you can think through most anything.' In my first History and Philosophy of Science class, I read Kant. I also find immense happiness in working with and helping other individuals, a sense of euphoria matched by little else in life. I learned this lesson through tutoring students and coaching younger athletes. And finally, as a collegiate athlete myself, I have undergone multiple orthopedic surgeries that ignited an interest in the musculoskeletal system and its ability to suffer injury yet recover remarkably. Together, these three aspects of life are central to my vision of the future. Becoming an orthopedic surgeon is the perfect combination—the career that will give me these components and a lot more.

One of the major developments in medicine will be 3-D printing, primarily in order to provide individuals with replacement bones and organs. Combining new progress in computer science will facilitate immense progress in 3-D printing, which also aligns well with the use of robotics in surgery. As an athlete who has torn my ACL and had bone spurs in the past year, I'm excited to be a part of this field in the future and hopefully help other athletes succeed in pursuing their passions."

Harinee Maiyuran
BS in History and
Philosophy of Science



Yubo Su
BS in Physics and Computer
Science



“My personal hunch, and perhaps a somewhat common one, is that all disciplines—and not just STEM ones—are moving toward being increasingly data driven, a phenomenon rooted in freer dissemination and greater influx of research data. Correspondingly, computers and programming drive data processing in all disciplines; a common joke is that every scientist is automatically a software engineer. Statistical and machine learning techniques that are designed to tackle vast quantities of data are increasingly common in academic papers and will probably continue to climb in popularity.

I am planning to go into computational astrophysics research because I believe that the recent influx of data from new detectors will drive a huge surge of research questions to be investigated. And as a physics/computer-science double major, I'm uniquely equipped to analyze big data and extract scientific meaning from it.”

“Many aspects about future climate are unclear, such as how cloudiness, precipitation, and extreme events will change under global warming. But recent progress in observational and computational technology has provided great potential for clarifying these uncertainties. I plan to continue my research and utilize new data and models to develop theoretical understanding of these problems. I hope that such new insight will be helpful for assessing climate change impacts and designing effective adaptation and mitigation strategies.”

Zhihong Tan
PhD in Environmental Science and Engineering

“The future of science and engineering depends on closing the huge gap between the general public and scientists and engineers. I think this stems from a good deal of ignorance about what it is we do and hope to achieve, which leads to misconceptions about our work and community, and the separation between 'us' and 'them.' But if we're trying to understand and solve problems that affect everyone, shouldn't everyone be more involved?

When I graduate, I'm going to take a year off to try and bridge this gap in my own life. I don't know what I'll do yet, but it will be decidedly nonacademic. I want to travel, work odd jobs, and pursue hobbies I've set aside to finish my education. If I want to help people understand why I do what I do, I need to be certain that I understand first. After only four years surrounded almost exclusively by scientists and engineers, I want to get away a little. That way, when I inevitably return, I'll have a bit more perspective.”

Valerie Pietrasz
BS in Mechanical Engineering and Planetary Science

“Driven by the goal of reducing fossil fuel use and pollution, clean energy research plays and will play a pivotal role in America’s energy future. Clean energy research spans disciplines such as biological and environmental sciences, advanced materials, nuclear sciences, and chemistry. Therefore, multidisciplinary efforts are not only necessary but also crucial to develop and deploy real-world solutions for energy security and protecting the environment.

As a graduate student, I have focused on understanding nanoscale energy transport in novel energy-efficient materials. In the future, I plan to further advance and apply my expertise to solve real-world problems in an integrated and multidisciplinary approach. I hope this effort will eventually lead to developing advanced clean energy technologies that could not only ease today’s energy crisis but also improve our quality of life.”

Chengyun Hua
PhD in Mechanical Engineering



“I believe that in the next decade, the behavioral and computational subfields of neuroscience will work together seamlessly. I think this change will be primarily fueled by the development of new tools that allow us to measure the activity of large populations of neurons more precisely.

A prominent behavioral method of research, in mice at least, is to activate large structures in the brain and observe the aggregate behavioral effect. However, it is unlikely that all of these neurons are responsible for the same signal, so this approach may be too crude. I think new measurement techniques will enable behavioralists to collect large-scale population activity that computationalists can use in order to find subtle differences of function within these structures. Hopefully this collaboration will lead to generating and validating fundamental theories underlying how the brain works.

Currently, I am in the process of developing a method to measure the activity from over 10,000 neurons simultaneously. I hope to validate this technique before I graduate and then apply it to studying large-scale population activity during various behaviors. My future aim is to work closely with computationalists with the hope of discovering fundamental theories of brain function.”

Gregory Stevens
BS in Biology

“I think the future of planetary science is to discover and characterize more and more extra-solar planets, including their orbital configurations, atmospheres, and habitability. This is a challenging task because it requires a solid understanding of how chemistry and physics work on a planetary scale. Learning more about the planets closest to us paves a way toward the understanding of exoplanets that are far beyond our reach, since we can send missions to them. So after graduation, I will join the team for Juno—the spacecraft that will arrive at Jupiter in summer 2016—at JPL. New discoveries about Jupiter will also tell us more about what other planets beyond our solar system could look like.”

Cheng Li
PhD in Planetary Science
eSS

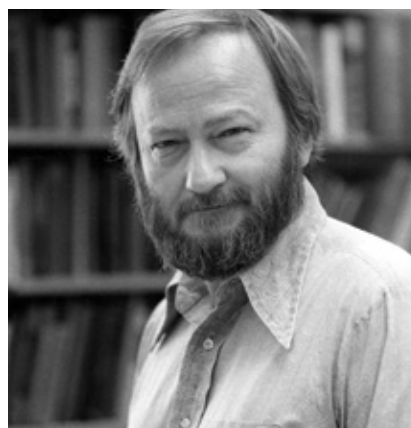
David G. Harkrider 1931-2016

David G. Harkrider, professor of geophysics, emeritus, at Caltech and an expert in seismological wave propagation, passed away on February 18, 2016. He was 84.

Born on September 25, 1931, Harkrider received his bachelor of science degree from Rice University in 1953 and his master of arts degree in 1957. He earned a doctorate in geophysics from Caltech in 1963. He joined the Department of Geology at Brown University as an assistant professor in 1965. He returned to Caltech as an associate professor in 1970, becoming a professor in 1979 and a professor emeritus in 1995. From 1977–1979 he was the associate director of Caltech's Seismological Laboratory.

Harkrider was president of the Seismological Society of America in 1988.

Harkrider investigated diverse topics within the field of geophysics. Early in his career he studied the theory of air-wave trains—the oscillations of the atmosphere in regions experiencing strong shocks, such as a meteor or nuclear explosion. At Caltech, he collaborated with Professor of Geophysics Donald Helmberger and then-Professor of Geophysics Charles Archambeau (now a retired professor of physics at the University of Colorado) to analyze and interpret the propagation of seismic waves in the earth. Harkrider's work was focused on the analysis of the propagation of surface waves—a type of seismic wave that travels through the crust—and their coupling with air waves and tsunami waves. He led the development of a digital computing system to recognize the seismic signals from



earthquakes and to rapidly determine their locations.

Harkrider is survived by his wife, Sara Brydges; daughter, Claire; and son, John.

To learn more about Harkrider's life and work, visit caltech.edu/news/geophysicist-david-g-harkrider-dies-49862.

The Honorable Shirley M. Hufstedler 1925-2016

The Honorable Shirley M. Hufstedler—a former federal judge, the nation's first secretary of education, and a Caltech senior trustee—passed away on March 30, 2016, in Glendale, California. She was 90.

Hufstedler received her bachelor of business administration degree from the University of New Mexico in 1945 at the age of 19, and her law degree from Stanford University in 1949.

After a decade in private practice in Los Angeles, she served for a year as special legal consultant to the attorney general of California in regard to Colorado River litigation before the U.S. Supreme Court. In 1968, President Lyndon B. Johnson appointed her judge of the U.S. Court of Appeals for the Ninth Circuit, where she served for 11 years. In 1981 Hufstedler left public service and began teaching and practicing law.

Hufstedler first served on Caltech's Board of Trustees from 1975 to 1979. She was reelected to the Board in 1981, following her service as the first United States Secretary of Education. In total, Hufstedler was a member of the Caltech Board of Trustees for 39 years. As chair of the Board's Jet Propulsion Laboratory Committee, she was an advocate for JPL missions and programs. Additionally, Hufstedler was an adviser to the broader Caltech community on a variety of diverse topics such as women's issues and student life, the latter of which led to the Moore-Hufstedler Fund being created in her honor.

She is survived by her husband of 66 years, Seth Hufstedler, whom she met while both were law students at Stanford; her son, Steven Hufstedler; and three grandchildren.



To learn more about Hufstedler's life and work, visit caltech.edu/news/honorable-shirley-m-hufstedler-1925-2016-50477.

We asked alumni: **What will be the next big thing in science or engineering?** Here's what some of them came up with.

AUTOMATED HIGHWAY SYSTEM:

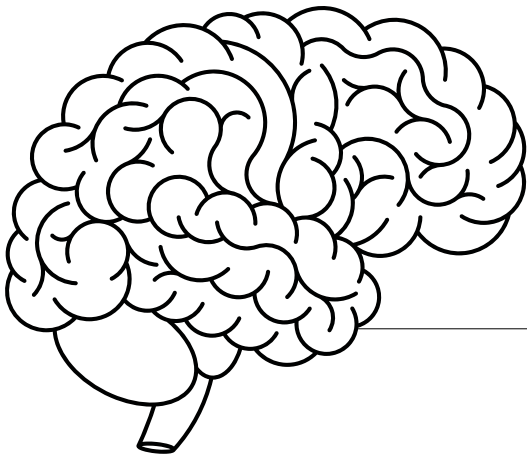
The improved efficiency, coupled with the number of lives saved, would position the nation for a new era of urban planning and growth.

I'd like to say cold fusion or a cure for cancer, but it's more likely to be a neural implant **enabling people to shop in their sleep.**



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The next big things in science are **DIGITAL TOOLS**, which are game changers in how we scientists process our knowledge and how we share it.



The tools, techniques, and results of **brain science research** will become prevalent in our future everyday lives, much like resources from the space race era impact our lives today.

Widespread use of **ARTIFICIAL INTELLIGENCE TECHNOLOGY** for improving health care, food, education, finance, transportation, energy, climate, robotics, and maybe even our understanding of how our minds work.

Civil engineering will become big again as California searches for **INNOVATIVE WAYS TO STORE WATER** in wet years for the inevitable dry ones.





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