Fall 2021

Caltech magazine

How Water Works

(and why it matters)

Inside the $3.4 billion *Break Through* campaign

Contents

Features

Departments

Left: Freshman Summer Research Institute (FSRI) students were among the first to return to campus in August. The FSRI program was created and is funded by the *Break Through* campaign. Pictured (front, from left): Michelle Li; Aija Washington; Monique Thomas, program manager for advocacy and campus relations; and Chi "Cellie" Cap. Back, from left, photographer Van Urfalian and art director Jenny Somerville.

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Patrick Almhjell, a graduate student in biochemistry and molecular biophysics, tweeted this photo of sunset over Beckman Auditorium.

Letters

The Success of Failure

At the Thomas Edison Museum near his winter retreat in Ft. Myers, Florida, there is a plaque that quotes him: "I have not failed. I've just discovered 10,000 ways that won't work."

—Van Snyder, JPL

Congratulations on the story about why failure is a good thing. It is probably the most important thing our faculty, leadership, students, and graduates need to understand.

—Carver Mead (BS '56, MS '57, PhD '60)
Caltech's Gordon and Betty Moore Professor of Applied Science, Emeritus

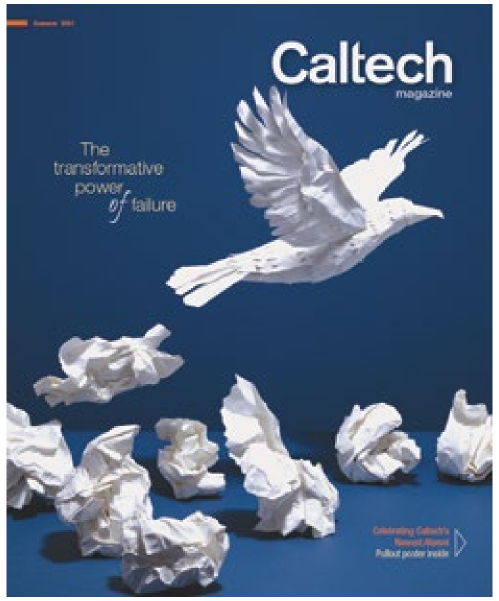
Insightful discussion of "failure" in the Summer 2021 issue. The word "failure" implies sub-optimal performance, or lack of correct action. But as your excellent article clarifies, "failure" is simply an intermediate and inevitable result in the process of posit, design, test, and evaluate. This process is necessary to make anything new, let alone achieve radical breakthroughs.

In my experience, many organizations undertaking a new project assume that the future is essentially knowable and try to limit the impact of unforeseen events by planning projects with periodic evaluation and adding a buffer of time to "fix things."

More recent thinking in project management acknowledges that the future is not knowable, but rather the team moves forward in small chunks of time and adjusts plans continually as they go. Essentially, failure is prevented by frequently resetting the expectations of everyone, including the project's sponsors.

—Paul Snyder (EX '80)

Thank you for your article on "The Transformative Power of Failure." It makes me appreciate all the innovative work being done at Caltech and knowing some of the dedicated professors who truly are



trying to make a difference. There are no overnight successes; one small success is generated from a million failures. We need to remember that in our everyday lives.

—Marisu Jimenez

Learning from Our Own Failures

There is a glaring error on page 17 of the summer 2021 issue. In the middle of the page, in bold print with an arrow pointing to it is the startling statement that mass equals length: "Planet Nine would have a diameter 2 to 4 times the Earth's mass." If you pick the right units (albeit strange ones in many cases), virtually everything has a diameter that is 2 to 4 times the Earth's mass, including the Earth's diameter itself.

—Keith Koenig (PhD '78)

Editor's note: And right at the beginning of our story about failure, too! You are right; what that statement should have said is, "Planet Nine would have a mass 5 to 10 times that of Earth." We regret our error.

I received several positive responses from our alumni community [on "Behind the Vaccine: A Conversation with Satoshi Ohtake (BS '00)"], many from new acquaintances, so thank you for providing me with the opportunity. I did note an error regarding my graduate degree; Washington should be Wisconsin.

—Satoshi Ohtake (BS '00)

Editor's note: Satoshi Ohtake graduated from the University of Wisconsin in 2005. We regret the error, and have corrected it in both the online version of the story, and in the archived PDF of the issue.

An Invigorating Issue

Let's not mince words: this *Caltech* magazine is fun to read, and stimulating.

—Tom Smith (BS '61)

My daughter graduated from Caltech and I was reading the articles in your Summer 2021 issue.

I teach Honors and AP chemistry, and would like to use "If at First... The Transformative Power of Failure" during my beginning days of class. Last year our school was remote through about January. Many students never came back; one AP chemistry class had two in-person students out of about 30! So, instead of jumping into facts, I would like to explore science, and to use this article to set the stage for the year. I am also Science Olympiad head coach and would like to share that article with our team.

There is a passage in "Biology Through the Eyes of a Physicist" that talks about a cell not caring if you were a biology, chemistry, or physics major—it uses all of those! "Sustainability Solutions" can be used to kick off our electrochemistry unit. "Behind the Vaccine" could be used for gaining a fundamental understanding of science and then move on and adapt.

So many uses for many of the articles!

—Margaret Stokes-Chinetti

In Flight

I was a postdoc with [the late biologist] Seymour Benzer and enjoy keeping up with what's happening at Caltech. The July issue of the magazine struck me. A few years ago, my daughter made a paper sculpture of two birds (at right).

I guess that I just wanted to share.

—John A. Pollock (Postdoc '84-'89)

Specimen: Phoenix. Paper, wire, paint, polymer clay, natural wood. Isel L. Pollock - 2017

SoCaltech

A Different Take on the Turtle Pond

In *Turtle Pond* (2019), a Caltech landmark gets a modernist makeover with a little help from artificial intelligence. Tomas Aquino, a graduate student in the lab of Fletcher Jones Professor of Psychology John O'Doherty, used a machine learning platform called PyTorch to create this piece of art. The system works by assessing the essentials of just one example of a particular style of art, after which it can transfer those characteristics onto another image.

Aquino and colleague Sanghyun Yi, a graduate student in social science, applied the essential look of the work of Brazilian artist Tarsila do Amaral to a photograph of Throop Pond, Caltech's iconic water feature. The resulting image was displayed as part of the 2019 Caltech *Art of Science* exhibit. "I am originally from São Paulo, where Tarsila established herself as one of the most influential Brazilian artists ever," Aquino says, "so her style was a natural choice for me."

In a recent study, Aquino, Yi, and their fellow researchers in the O'Doherty laboratory used a similar system to demonstrate that artificial intelligence can not only determine the essential elements of a visual style—be it impressionism, realism, or abstract—but also can predict whether a person will like a particular painting based on their previous preferences.

▸ See "The Art of Predicting Tastes in Art" on page 32.

Three Questions for:

Mitch Aiken

Earlier this year, Mitch Aiken, the associate director for educational outreach at the Center for Teaching, Learning, and Outreach (CTLO), oversaw the expansion of the Summer Research Connection (SRC) through the launch of the new Hybrid Summer Research Connection (HSRC). Aiken explains how HSRC will allow more Southern California high school students to connect with Caltech.

1. How have you made Caltech's summertime outreach programs work remotely?

It's been a challenge these last two summers. Many of our groups are doing laptop-based research, using their coding skills to study data, develop website apps, and conduct research online. For the students who are particularly interested in chemistry or biology, in some cases we've been able to supply kits that allow them to engage in hands-on research.

The critical piece has been to make it not feel like school. Typically, when a student comes to campus, it's a special experience that wouldn't be happening in the classroom. We've tried to make sure that the remote components are as engaging and collaborative as possible and not so content-heavy that the students feel like they're in summer school.

2. What kind of research can students work on from home?

With [Gordon M. Binder/Amgen Professor of Biology and Geobiology] Dianne Newman's group, we did an activity with MudWatts, which are devices that detect energy from microbes in mud. Students tried varying samples of mud with different concentrations of water, and they tested which ones contained microbes that generate energy—enough to light a light bulb or power an electronic digital clock. Other groups worked on their laptops, analyzing data from telescopes; this gave them the real sense of being on a path of discovery.

3. What do you hope to accomplish with CTLO's outreach mission?

We want to get students, particularly those who are historically marginalized in STEM fields, excited about STEM.

There are all kinds of paths into science. We don't see our efforts as a direct recruiting path to Caltech, but a recruiting path into the world of STEM. We have always focused on diversity, equity, and inclusion in all our educational outreach programs and continue to view our programs through this lens.

Read more about CTLO at **ctlo.caltech.edu**

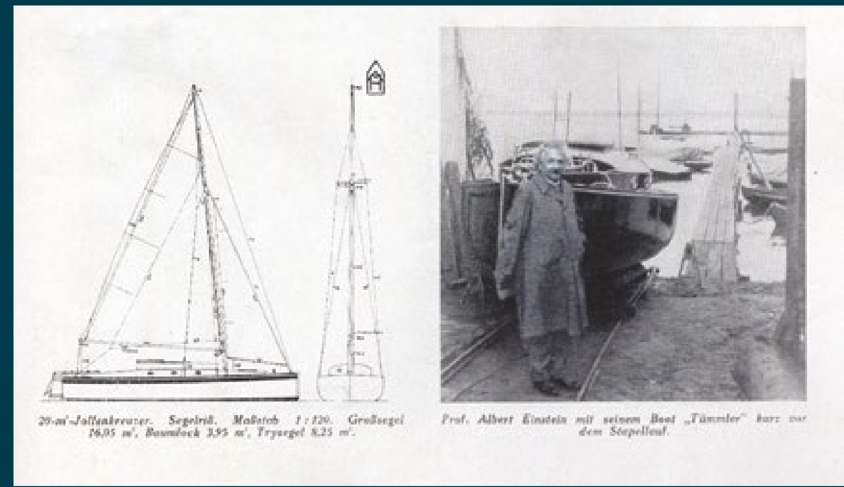
Einstein's Sailboat

When Albert Einstein turned 50 on March 14, 1929, he received a flood of congratulatory wishes. Many of the letters pertained to a birthday present Einstein cherished the most: a single-cabin sailboat, named *Tümmler*, which means porpoise in German.

The Einstein Papers Project at Caltech has released the 16th volume of its massive scholarly collection of the famed physicist's scientific and nonscientific writings and correspondence, in which these documents appear. The volume covers the period from June 1927 to May 1929 and contains 1,600 letters by and to Einstein, many more than contained in previous volumes.

Aside from enjoying his sailboat, Einstein had one great wish for his milestone birthday, according to Diana Kormos-Buchwald, Caltech's Robert M. Abbey Professor of History and director of the Einstein Papers Project: "He wanted to avoid the press, the visitors, the fanfare, and the tributes. He escaped Berlin for the countryside," she says.

Read Volume 16 of *The Collected Papers of Albert Einstein* at **einsteinpapers.press.princeton.edu**

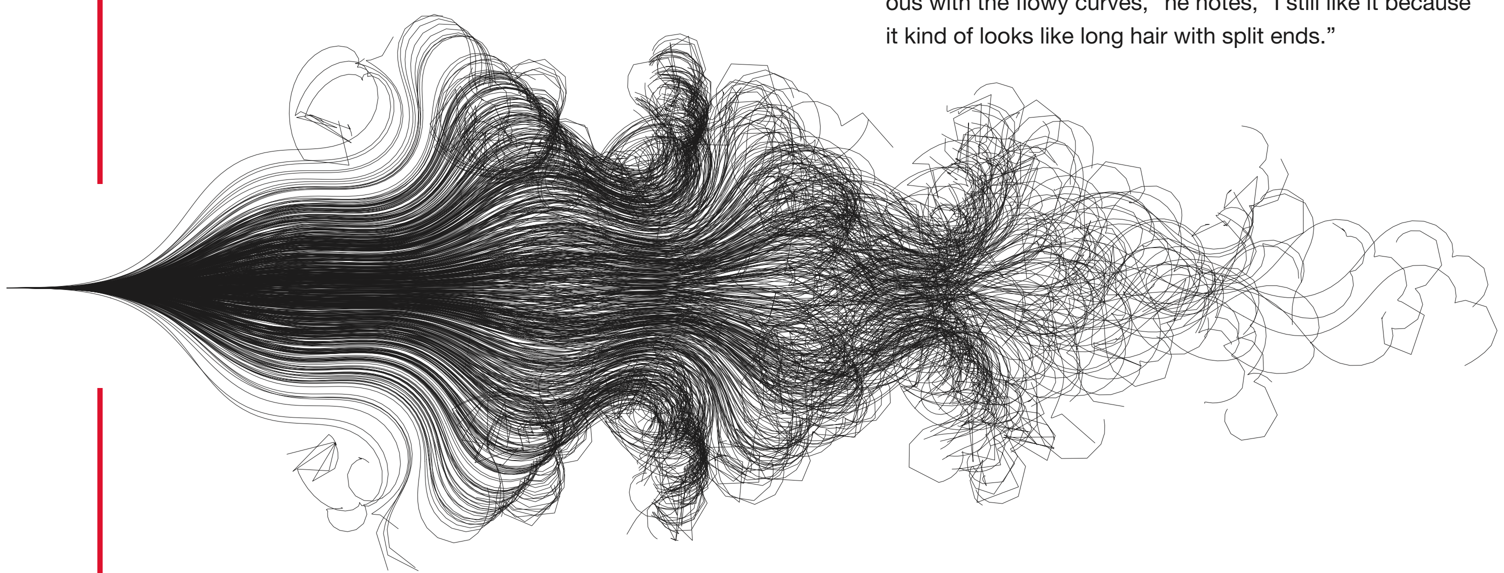


Riderless Bicycle

In 2004, while a graduate student at Caltech, Matthew Cook (PhD '05) created this evocative illustration that shows various paths a bike with no rider might take before it falls over. Developed as part of a study of how artificial intelligence might learn to ride a bike, the visualization has resurfaced and spread on social media numerous times since its publication.

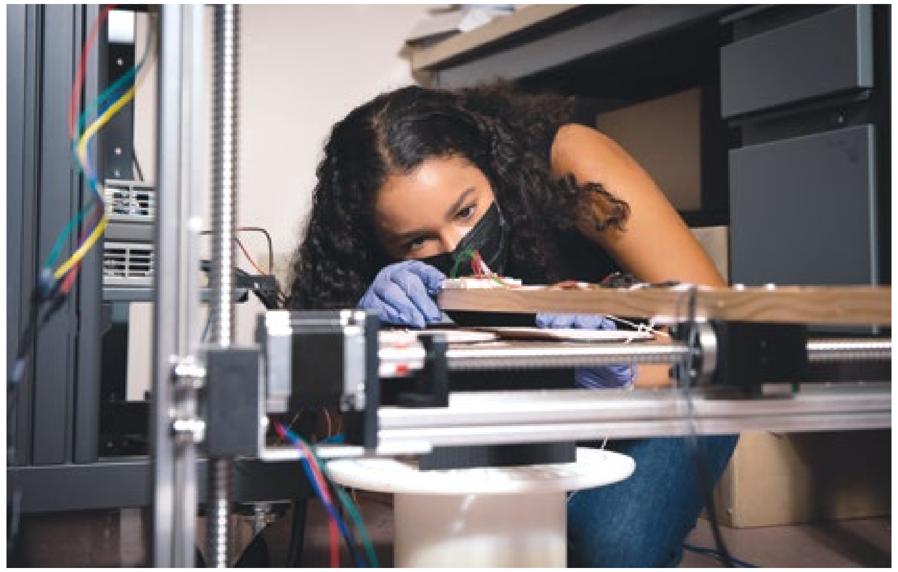
Each line represents one of 800 simulator runs, each of which ends when the riderless two-wheeler topples. The curves that end in straight segments correspond with paths in which the wheels become horizontal as the bike topples over, which leads to large distances between the points where the wheels touch the ground from instant to instant.

Cook, who recently returned to Caltech as a visiting Moore Distinguished Scholar while on sabbatical from the Institute of Neuroinformatics at the University of Zurich and ETH Zurich, says he receives a flurry of emails about the illustration every few years when it reappears on social media. "Although the segments are visually incongruous with the flowy curves," he notes, "I still like it because it kind of looks like long hair with split ends."



A Summer of *SURFers* and *WAVEs*

After a year of remote learning because of the COVID-19 pandemic, a group of 318 undergraduates were brought back to campus this summer to participate in the Summer Undergraduate Research Fellowships (SURF) and WAVE Fellows programs. Through SURF, Caltech undergraduates can conduct 10-week research projects with faculty; WAVE aims to promote the participation of underrepresented undergraduate students in science and engineering and, like SURF, allows students from other institutions to do summer research at Caltech. “I had never done any research or worked in a scientific setting before the SURF program,” says Caltech sophomore Rahul Chawlani. “I learned not only how research works but also how to manage responsibilities in a workplace and lab.”



MIT junior **Liliana Edmonds** delicately moves a magnetic sensor 1 millimeter at a time as part of a WAVE project in collaboration with **Azita Emami**, Andrew and Peggy Cherng Professor of Electrical Engineering and Medical Engineering and director of the Center for Sensing to Intelligence. Edmonds was focused on methods to improve researchers’ and clinicians’ ability to locate and position trackable microscale devices inside the body. The goal is to improve the effectiveness of precision surgeries and medical procedures.

Over the summer, SURFer **Rahul Chawlani** (left) turned up the heat to study the composition of rock samples from the Great Oxygenation Event, a period more than 2 billion years ago when Earth’s atmospheric oxygen spiked. In collaboration with **Claire Bucholz**, assistant professor of geology, he warmed the samples in an oven that reached more than 1,000 degrees Celsius to remove trapped water and obtain a pure sample of the rock.

As part of her SURF project, Caltech junior **Diana Frias Franco** (left) designed and built an instrument to measure the torque exerted on a sample of smart fabric, an engineered wearable material that senses environmental stimuli and responds to varying conditions with changes in mechanical properties such as stiffness. She worked with **Chiara Daraio**, G. Bradford Jones Professor of Mechanical Engineering and Applied Physics.

Caltech sophomore **Ann Zhu** worked with **Mikhail Shapiro**, professor of chemical engineering, on a SURF project to improve the diagnosis of inflammatory bowel diseases and pinpoint sites of inflammation. She engineered *E. coli* bacteria to express certain protein nanostructures that the researchers can image in the lab.

Caltech junior **Tyler Nguyen** (second from right) worked on his SURF project with **Mory Gharib** (PhD ’83), Hans W. Liepmann Professor of Aeronautics and Bioinspired Engineering as well as Booth-Kresa Leadership Chair and director of the Center for Autonomous Systems and Technologies, on a fish-inspired robot that can propel itself through water and could one day be used to explore extraterrestrial ocean worlds.

Grace Liu (junior)

#SoCaltech is an occasional series celebrating the diverse individuals who give Caltech its spirit of excellence, ambition, and ingenuity. Know someone we should profile? Send nominations to ***magazine@caltech.edu.***

Grace Liu, a junior in biology and biological engineering, discusses her Summer Undergraduate Research Fellowship (SURF) experience in the laboratory of Nobel laureate Frances Arnold, Linus Pauling Professor of Chemical Engineering, Bioengineering and Biochemistry and director of the Donna and Benjamin M. Rosen Bioengineering Center. Liu uses machine learning to predict how certain proteins will interact to catalyze chemical reactions.

"I was working with the Arnold Lab earlier in the school year, but I always felt like the undergrad among grad students. Now, thanks to my SURF, I've merged into the lab a lot more. I go to group meetings, and I can have conversations with the grad students, who are always telling me about papers and new packages of code that might be helpful to my research.

"When I'm doing a SURF, because I'm trying to tackle a bigger project, it has surprised me how many things I have to work on at once. While coding, for example, I will run into a problem and must find a way around it. But then finding a way around it requires me to use a new technique, or use a new package, or learn something new altogether. It's a much more dynamic process. It's constantly changing."

For more #SoCaltech, go to magazine.caltech.edu/post/socaltech

Alumnus Ardem Patapoutian (PhD '96) Wins 2021 Nobel Prize in Physiology or Medicine

Caltech alumnus Ardem Patapoutian (PhD '96), Presidential Endowed Chair in Neurobiology and Professor at Scripps Research in La Jolla, California, and a Howard Hughes Medical Institute Investigator, won the 2021 Nobel Prize in Physiology or Medicine, sharing the award with David Julius of UC San Francisco. The two were honored for their "discoveries of receptors for temperature and touch," according to the award citation.

The sense of touch is shaped by sensory information related to both temperature—hot or cold—and pressure. Patapoutian and Julius made major contributions that helped to uncover how these processes work and to elucidate how temperature and pressure stimuli are converted into electrical impulses in the nervous systems. Their work is now leading to new treatments for chronic pain, including the development of non-opioid painkillers.

Patapoutian was honored for his discovery of the cellular sensors in the skin and internal organs that respond to mechanical stimuli such as touch. He and his collaborators first cultured a cell line that gave off a measurable electrical signal when individual cells were poked with a tiny pipette. The team systematically knocked out individual genes in these cells, which allowed them to identify the genes that encode for the receptors that respond to pressure.

As a graduate student at Caltech, Patapoutian worked in the laboratory of Barbara Wold (PhD '78), Bren Professor of Molecular Biology and Allen V. C. Davis and Lenabelle Davis Leadership Chair and director of the Richard N. Merkin Institute for Translational Research. "This is a joy to see," Wold says. "Ardem came with a great love of biology, zest for discovery, and capacity for fine experimental design. And he was always willing to go an extra mile when it required pure work."

"The way genes are regulated—how they are dialed up or turned down—is the basis underlying complexity and cellular function. Much of this process is mediated by proteins that do not have clear shapes. These proteins are so difficult to understand because they don't fold into well-defined structures, and cannot be understood by conventional analytic methods. The 'dark proteome' is another name for these structures. They can be thought of as the dark matter of biology because they make up a large portion of our bodies' proteins and play many roles in our bodies, but we know very little about them."

—Shasha Chong, who recently joined Caltech as assistant professor of chemistry and is a Ronald and JoAnne Willens Scholar

Read Chong's full profile at **www.caltech.edu/chongqa**

2021–2022 Watson Lectures to be Presented via YouTube Live

Last year, due to the coronavirus pandemic, the Earnest C. Watson Lecture Series was presented virtually for the first time. That unexpected shift allowed Caltech's global community to attend the lectures and engage remotely with the cutting-edge research conducted by Caltech faculty.

To continue this reach, the 2021–2022 Watson Lecture Series will be livestreamed via YouTube Live so that viewers can watch and interact virtually no matter where they are.

The season lineup will feature faculty from across Caltech's academic divisions and JPL and cover such topics as artificial intelligence, quantum matter, the long history of managing public uncertainty around health and science, efforts to measure sea level changes, quantum entanglement, life-saving polymers, and more. Visit **caltech.edu/watson** to register to attend, sign up for timely notification of upcoming lectures, and watch past lectures.

"The Caltech Center for Inclusion and Diversity (CCID) team will work with community members to develop realistic goals incorporating inclusive, diverse, equitable, and accessible frameworks and practices to move toward a culture change. I will also prioritize the Institute's goal of 'a more Inclusive Caltech' by working to identify gaps in our support of historically excluded groups in the Caltech community while strengthening programs and resources that have proven to be successful for historically excluded groups."

—Tashiana Bryant-Myrick, *the new director of CCID*

Read her full profile here:

Object Lesson: Feynman Diagrams in Space

One of NASA's newest spacecraft to reach orbit features artwork that is close to home: stylized depictions of Feynman diagrams, laser-etched into the outer emissivity skin of the PACE-1 6U satellite.

The PACE-1 satellite is part of NASA's Payload Accelerator for CubeSat Endeavors (PACE) Initiative, a project to test a series of potential payloads for cubesats, which are tiny modular satellites. In addition to its scientific mission to assess how well certain technologies can survive the harsh environment of space, PACE-1 features an orbital art exhibition. Artists Arno Geens, Selby Sohn, Mike Dabro, and Steven M. Johnson each created work that was specially commissioned for this mission, then curated and integrated by NASA Ames Spacecraft Systems Designer Luke Idziak.

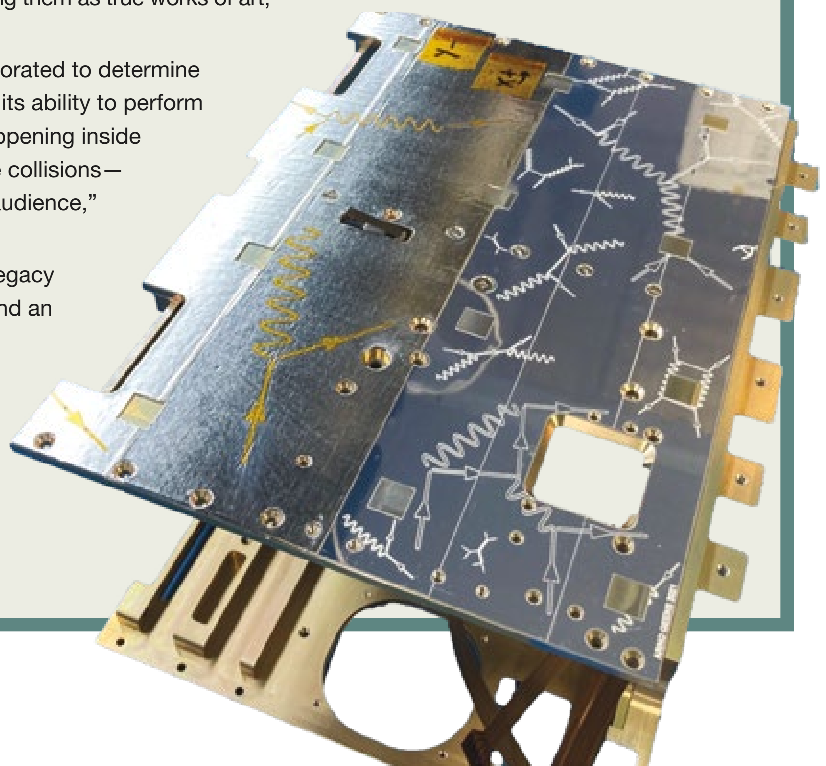
Geens, a designer and former visual strategist at JPL, which Caltech manages for NASA, created the section of the artwork that drew inspiration from diagrams created by the late Richard Feynman, professor of physics and Nobel laureate.

"Feynman developed a uniquely elegant and creative visual language to depict an intrinsically complex process," Geens says. "His diagrams depict the interaction of subatomic particles, such as the kind that would occur from radiation affecting a satellite's scientific payload. By honoring them as true works of art, his diagrams directly reflect the satellite's objective."

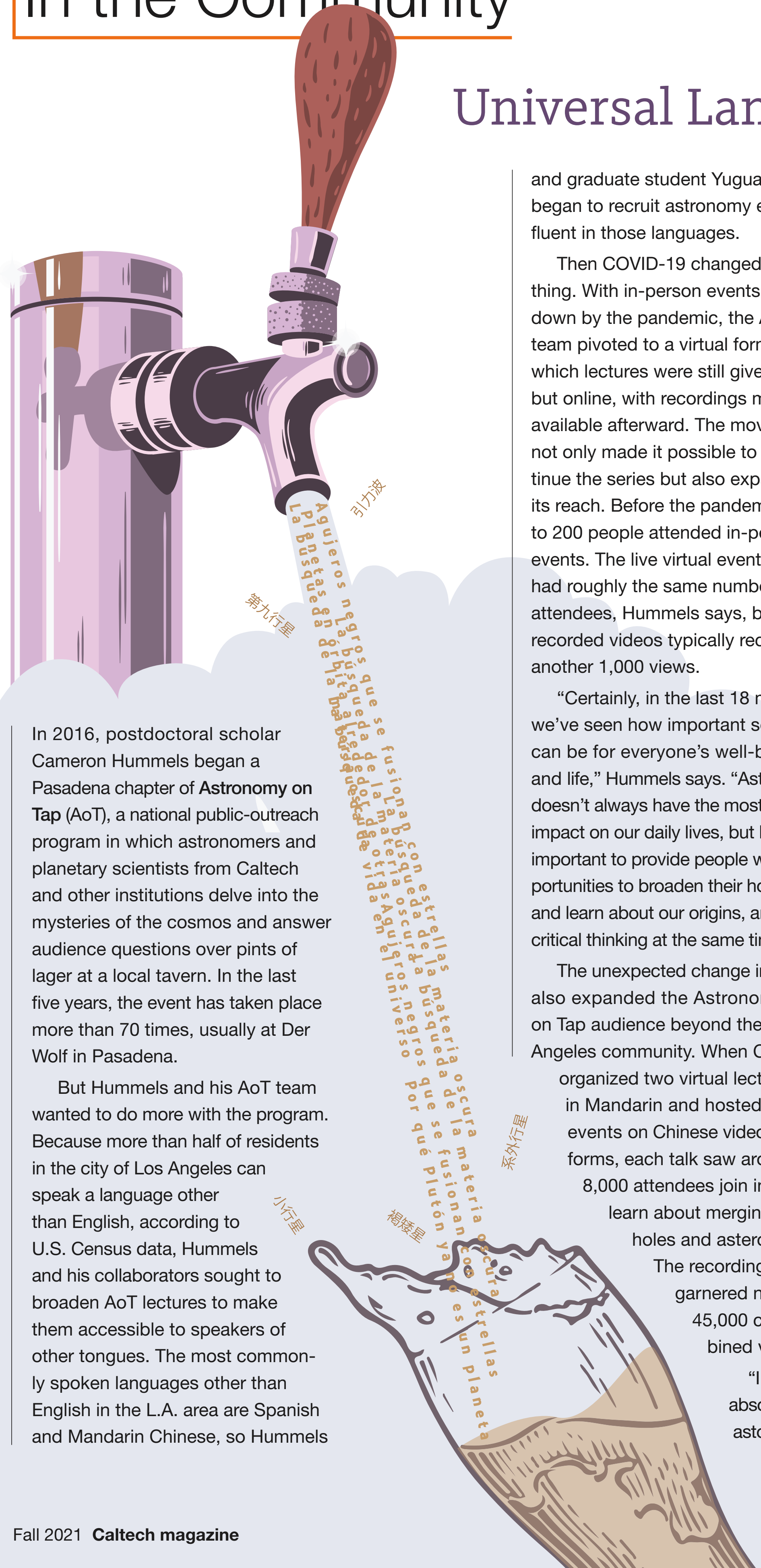
The spacecraft engineering team, artists, and Idziak collaborated to determine how to etch art onto the side of the cubesat without affecting its ability to perform its job. "We wanted to find a way to depict invisible things happening inside the spacecraft; to show vanishingly small processes—particle collisions—through an artistic medium that could be accessible to wide audience," he says.

Idziak sees the artwork as both a continuation of NASA's legacy of art in space, which includes the Voyager Golden Record, and an homage to the bygone era of objects that are functional and creative, such as illuminated medieval manuscripts.

"Every spacecraft is a custom-built creation, with countless hours of effort distilled into it," Idziak says. "By including artists in the development process, we have an opportunity to make new spacecraft not only functional, but beautiful and engaging to a wide audience as well."



Universal Languages



In 2016, postdoctoral scholar Cameron Hummels began a Pasadena chapter of **Astronomy on Tap** (AoT), a national public-outreach program in which astronomers and planetary scientists from Caltech and other institutions delve into the mysteries of the cosmos and answer audience questions over pints of lager at a local tavern. In the last five years, the event has taken place more than 70 times, usually at Der Wolf in Pasadena.

But Hummels and his AoT team wanted to do more with the program. Because more than half of residents in the city of Los Angeles can speak a language other than English, according to U.S. Census data, Hummels and his collaborators sought to broaden AoT lectures to make them accessible to speakers of other tongues. The most commonly spoken languages other than English in the L.A. area are Spanish and Mandarin Chinese, so Hummels and graduate student Yuguang Chen began to recruit astronomy experts fluent in those languages.

Then COVID-19 changed everything. With in-person events shut down by the pandemic, the AoT team pivoted to a virtual format in which lectures were still given live but online, with recordings made available afterward. The move online not only made it possible to continue the series but also expanded its reach. Before the pandemic, 100 to 200 people attended in-person events. The live virtual events have had roughly the same number of attendees, Hummels says, but the recorded videos typically receive another 1,000 views.

"Certainly, in the last 18 months, we've seen how important science can be for everyone's well-being and life," Hummels says. "Astronomy doesn't always have the most obvious impact on our daily lives, but I think it's important to provide people with opportunities to broaden their horizons and learn about our origins, and teach critical thinking at the same time."

The unexpected change in plans also expanded the Astronomy on Tap audience beyond the Los Angeles community. When Chen organized two virtual lectures in Mandarin and hosted the events on Chinese video platforms, each talk saw around 8,000 attendees join in to learn about merging black holes and asteroids. The recordings have garnered nearly 45,000 combined views.

"I was absolutely astonished to see the enthusiasm among our audience," says Chen. "Thousands of people tuned in to our live events and participated in the Q&A session. It definitely encouraged us to organize more high-quality content in the future."

The Spanish-language events have featured researchers from Caltech and NASA discussing black holes, dark matter, and brown dwarfs (objects in between planets and stars in size). Two PhD students in astronomy and planetary sciences, Tony Rodriguez and Benjamin Idini (MS '19), have hosted these events and provide context and commentary.

"These events attempt to reach the full Spanish diaspora, with speakers from Mexico, Spain, and South America, and are timed so that all of the Americas can watch live," Hummels says.

The team plans to continue the the events and hopes to host talks four times per year in Spanish and four times in Mandarin in addition to the usual programs in English.

"We plan to achieve a balance between in-person and online events after the pandemic," says Hummels. "Online content reaches a much larger audience and is preserved for longer, but there's something special about interacting with people in an in-person intimate setting, so we'll try to have it both ways. This is all about just trying to reach more people regardless of nationality, regardless of cultural background."

– Lori Dajose

For a full list of upcoming Astronomy on Tap lectures, visit **outreach.astro.caltech.edu**, *or follow* **@CaltechAstro** *on Facebook, Twitter, Instagram, and YouTube.*

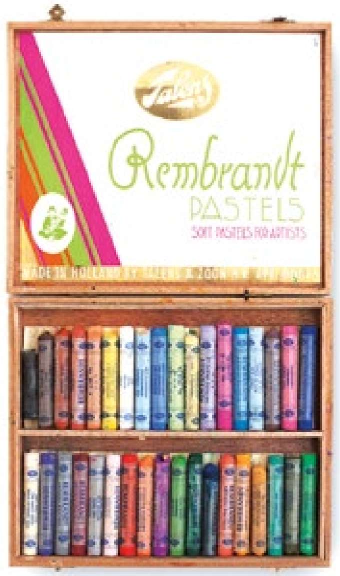
A Planet Painted by Hand

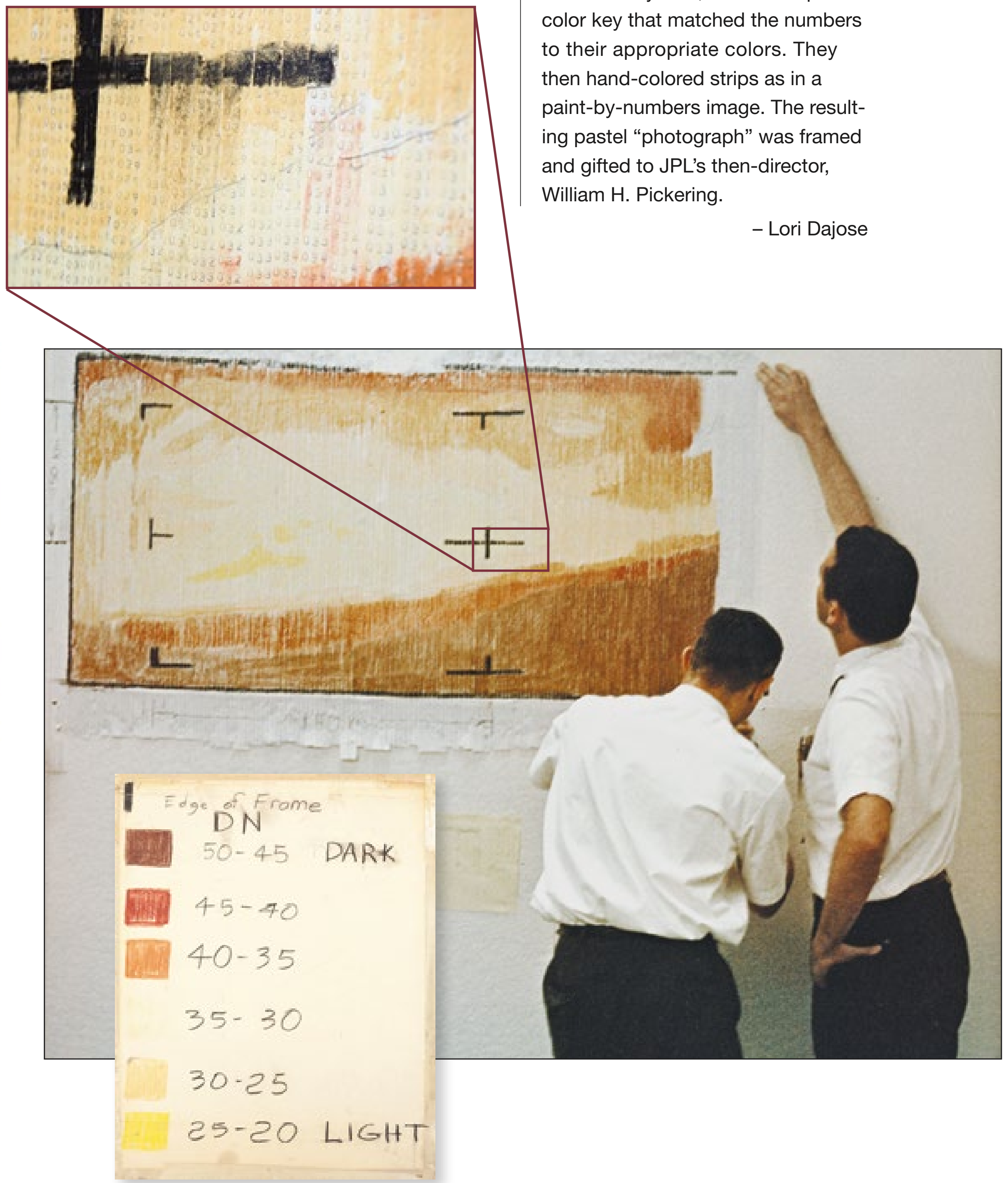
The *Perseverance* rover has sent more than a hundred thousand high-resolution images of the Red Planet since it landed on Mars in February 2021, which allows anyone with an internet connection to view photographs (including selfies) taken by a robot on another world. But it was not always so easy to obtain detailed images from another planet.

In 1965, the Mariner 4 mission flew by Mars and snapped 22 images of the planet using a television camera, the first pictures of the planet taken up close. The spacecraft relayed the raw numerical data back to mission control at the Jet Propulsion Laboratory (which Caltech manages for NASA), whose engineers could reconstruct these data into an image.

Impatient to see the official processed image, the telecommunications team rebuilt the picture themselves. They printed out the numbers on strips of paper, attached them side by side, and developed a color key that matched the numbers to their appropriate colors. They then hand-colored strips as in a paint-by-numbers image. The resulting pastel "photograph" was framed and gifted to JPL's then-director, William H. Pickering.

– Lori Dajose





The breakthrough Is Just the Beginning

At Caltech, a breakthrough may refer to breaking through boundaries to build collaborations across disciplines, to a landmark discovery or groundbreaking study, or to the **$3.4 billion campaign** that has catalyzed the creation of new technologies, tools, and innovations to address global challenges and improve the human condition.

"*Break Through* funding supports a level of creativity. And creativity in research leads to the really interesting, big discoveries."

— Cam Buzard, *a graduate student who studies hot Jupiters, gas giants that orbit very close to their host stars. Buzard is a Beckman-Gray fellow, an award supported by the campaign that allows scholars the freedom to follow their intellectual passions and research interests without being constrained by funding sources.*

Building for Innovation

Break Through gifts created 15 new centers and initiatives to build upon the Institute's interdisciplinary practice and transform the physical environment in the process. The **Tianqiao and Chrissy Chen Institute for Neuroscience at Caltech**, headquartered within the Chen Neuroscience Research Building, unites researchers across an array of disciplines who seek to deepen our understanding of the brain's structure and how the brain works at its fundamental level. The **Resnick Sustainability Institute** brings together research across campus that addresses challenges and opportunities associated with climate change and the stewardship of natural resources. The **Merkin Institute for Translational Research** empowers scientists and engineers to turn their breakthrough innovations into real advances in human health.

The campaign also allowed Caltech to revitalize the **Gates–Thomas Laboratory**, build the **Bechtel Residence**, construct a robotic wonderland to house the **Center for Autonomous Systems and Technologies (CAST)**, renovate the the **Ronald and Maxine Linde Hall of Mathematics and Physics**, and much more.

"Philanthropy allows you to take risks," says Caltech president Thomas F. Rosenbaum, holder of the Sonja and William Davidow Presidential Chair and professor of physics. "It allows you to **push the limits of your imagination.** And when it works, then, of course, **you have transformation.**"

"A small school isn't for everyone. It's for people who want opportunities to get involved and make a difference—and I want to help make sure that all students feel like this is the place where they can do that."

— Mason Smith (BS '09), *head of software engineering at TGS Management Company and Caltech young alumni trustee. Smith's campaign support has buoyed not only scholarships but also the Freshman Summer Research Institute (FSRI), a program for incoming students from underrepresented or underserved communities.*

During the *Break Through* campaign, donors invested more than $3.4 billion to position the Institute for a **future of limitless discovery** and Caltech became **the smallest undergraduate institution in the country to raise more than $3 billion.**

"Our undergraduate and graduate students are our backbone. They are the ones who actually do the work on the bench and make remarkable things happen."

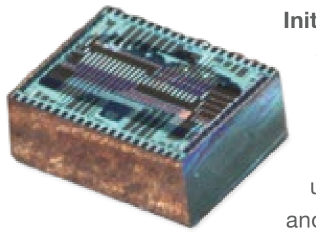
— Shu-oh Shan, *Altair Professor of Chemistry and member of Caltech's Center for Molecular Medicine, a collaboration at the interface of chemistry and biology made possible by* Break Through *funding from the Gordon and Betty Moore Foundation.*

A *Break Through* Boost

Campaign donors have created forward-looking programs to help Caltech scientists and engineers across diverse fields maximize the impact of their work through translation of their discoveries into new products and ventures that improve lives.

To honor Carver Mead (BS '56, MS '57, PhD '60), the Gordon and Betty Moore Professor of Engineering and Applied Science, Emeritus, and his pioneering approach to research and innovation, more than 200 donors inaugurated the **Carver Mead New Adventures Fund** to boost exceptional projects at an early stage of development. New Adventures awarded its first grants in 2017, and has since funded research into computational microscopes that can see beyond what is possible with light alone; wearable devices that continually monitor a person's health; and a study of entropy in the genome of the SARS-CoV-2 virus, providing insights into the virus's evolution.

Inventors and innovators must face the "valley of death," where patent problems, testing snags, and funding issues can derail an interesting idea. The late James Rothenberg, a former Caltech trustee, and his wife Anne Rothenberg created the **Rothenberg Innovation Initiative (RI²)** to provide up to two years of crucial support to help Caltech researchers get their ideas to market. This past year alone, RI² gave support to a flexible Band-Aid–sized instrument to continuously monitor body core temperature and to lensless, flat silicon chips to improve LiDAR (light detection and ranging) technology in self-driving cars and biomedical instruments. Since the program's inception, RI² grants have spurred 176 patents, 18 start-ups, and 40 disclosed inventions.



More than **14,500 donors**—including **9,400 alumni**, or more than 45 percent of living alumni—endowed **46 professorships**, **28 early-career professorships**, and **24 leadership chairs**, and amplified or established **15 institutes, centers, and research initiatives.**

Bridging the gap between medical innovations and bedside applications is the focus of the **Heritage Research Institute for the Advancement of Medicine and Science**, established at Caltech in 2015 with a gift from Caltech senior trustee Richard N. Merkin, MD. This new institute created a cohort of researchers, the Heritage Medical Research Institute Investigators, who focus on translational sciences and health technology. Among the recent advances made possible through this cohort are the discovery of a functional link between gut bacteria and Parkinson's disease as well as other neurological disorders, which may lead to new treatments for conditions ranging from inflammatory bowel disease to Alzheimer's, and the development of a prototype miniature device that could roam the body to diagnose and treat disease.

The campaign raised **$136 million** for undergraduate scholarships and **$275 million** for graduate fellowships.

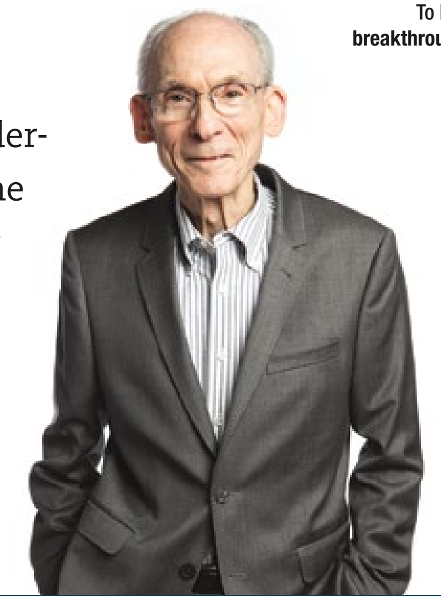
"Nobody cares whether you are a political scientist or a political economist or an anthropologist. At Caltech, you are judged by the answers you get, the mechanisms you discover, and their usefulness and reasonability."

— Marina Agranov, *professor of economics and member of the Center for Theoretical & Experimental Social Sciences (CTESS) within the Ronald and Maxine Linde Institute of Economic and Management Sciences.*

To learn more, visit **breakthrough.caltech.edu**

"I've been interested in supporting the Summer Undergraduate Research Fellowships (SURF) program from the beginning because I think it's an important opportunity for students to get the experience of working in a research environment as part of their education."

— Ed Stone, *David Morrisroe Professor of Physics and Vice Provost for Special Projects. As inspiration for his gift to support a SURF, Stone cited a student in the 1960s who realized that an alignment of the outer planets would make possible the Voyager missions, of which Stone served as project scientist.*

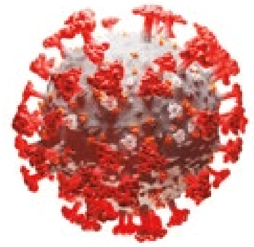


The breakthrough is just the beginning. The story of the *Break Through* campaign is one of seeding opportunities for **high-risk, high-reward research that will benefit society for decades to come.**

Points of Impact

Lasers Into the Brain: Lihong Wang developed a method called photoacoustic computerized tomography (PACT) that uses laser light and ultrasonic sound waves to image tissues and organs. This technology took a leap forward when a multi-university team led by Wang and including Andrew and Peggy Cherng Department of Medical Engineering staff scientist Konstantin Maslov showed that PACT can detect minute changes in the amount of blood traveling to different parts of the brain, thus measuring neural activity without many of the disadvantages of the ubiquitous functional magnetic resonance imaging (fMRI) machines, which are expensive and require patients to fit inside a narrow tube. Wang is Bren Professor of Medical Engineering and Electrical Engineering and member of the *Break Through*-supported **Andrew and Peggy Cherng Department of Medical Engineering**, Caltech's first named and endowed department, which backed this research.

Where the Sun Always Shines: Donald Bren, chairman of Irvine Company and a life member of the Caltech community, and his wife, Caltech trustee Brigitte Bren, donated $100 million to *Break Through* to support endowed professorships as well as the **Space-based Solar Power Project (SSPP)**. The project aims to build a prototype of an orbiting solar energy system that could collect the sun's rays all the time, with no worries about the effects of nightfall or cloud cover on the ability to take in energy. After converting solar energy to electricity, it would transfer that clean energy wirelessly back to Earth using radio frequency electrical power. The first test of the prototype is slated for 2023.



Chasing COVID: Pamela Bjorkman, the David Baltimore Professor of Biology and Bioengineering, has studied viruses such as HIV, but when COVID-19 brought the world to a standstill, researchers in her lab raced to apply their expertise to understanding SARS-CoV-2, the virus behind the pandemic. A team in the lab designed a nanoparticle-based immunization technique with the potential to protect against many kinds of coronaviruses. Another team characterized many different antibodies to SARS-CoV-2 and identified those most effective at neutralizing the virus. The *Break Through*-funded **Merkin Institute for Translational Research** supported this effort.

"I'm grateful to all who have decided Caltech is the place that deserves this very, very generous support, which provides us with **a firm foundation to go forward into unknown territories**," says David L. Lee (PhD '74), chair of the Caltech Board of Trustees.

Abdullah Ateyeh, pictured above, studies applied and computational mathematics.

Abdullah Ateyeh, Caltech Class of 2023

"Without my scholarship, I would not have been able to attend this world-class institution and immerse myself in the amazing extracurriculars and opportunities Caltech offers. I did research in astronomy—something I've wanted to do since I was a kid. I've made an amazing group of friends through Avery House, but also through the acapella group Out of Context. I'm extremely grateful for donor support for students like me. I can't wait to show the world that your investment in my future was well worth it."

Nick Hutzler, BS '07, Caltech Assistant Professor of Physics

"As a donor, alumnus, and faculty member, I now have a deep appreciation for the importance of unrestricted gifts to the Caltech Fund. Most donors want to fund the lasers; they want to fund the lab space. However, unrestricted funds cover everything else not paid for through grants—things that are vital, even if less exciting. We couldn't run our lasers or the lab without these other resources and people."

Nick Hutzler pictured with his wife, Caltech alumna Mary Wahl (BS '08) and their son, Isaac

When you give through the Caltech Fund:

- You invest in outstanding research and education
- You empower scientists to take risks that may yield remarkable outcomes
- You expand access to a Caltech education through scholarships
- You enhance the unique student experience
- You enable Caltech to address emerging opportunities

Your combined contributions to the Caltech Fund amplify the reach of every philanthropic dollar, stretching across the entire Institute in support of our mission of discovery and education. Thank you to all our donors who make this possible.

CaltechFund

Scan the QR code with your smartphone to **make your gift today.**

The 2021 Distinguished Alumni Award Recipients

Caltech's annual Distinguished Alumni Awards recognize "a particular achievement of noteworthy value, a series of such achievements, or a career of noteworthy accomplishment." The 2021 luminaries include a veteran NASA astronaut who helped lead a revival of American spaceflight; a chemistry alumna who invests in humankind's transition to sustainable energy sources; a former director of the Jet Propulsion Laboratory who oversaw decades of exploration; and a university president who traveled a winding path from expert on the composition of Mars to academic leader advancing research, education, and equity.

2021 DISTINGUISHED ALUMNI AWARD RECIPIENT

Robert Behnken

(MS ’93, PhD ’97, Mechanical Engineering)

NASA Astronaut

For his accomplished career as an astronaut on three space missions, including his history-making journey in 2020 as part of the first crew to reach Earth orbit aboard a commercially developed and operated spacecraft, as well as for his work as a public advocate for science and engineering.

Robert Behnken’s third trip into space began long before blastoff. It started with the opportunity to help shape a historic mission.

Not only did Behnken co-lead the 2020 mission aboard the SpaceX Crew Dragon capsule that became the first commercially operated craft to bring American astronauts to space, but he also worked with SpaceX in the months leading up to the launch to help define problems and identify the solutions that would make the flight a success.

“The technology is a critical aspect, but often the people who ride on it aren’t involved in the design,” he says. “We were pretty lucky to be connected to the development process.”

Coming into the project with an aggregate of about a month spent in orbit, not to mention six spacewalks, Behnken had ample experience to draw from. He also benefited from a tightly knit team, as the other astronaut on the SpaceX flight was his best friend, Douglas Hurley. Behnken says the camaraderie and hard-earned experience crew members share creates a familiarity that breeds efficiency. “You get to know what they’ll do in various situations,” he says.

Behnken credits the balance of curiosity and skepticism nurtured at Caltech for his outlook on life. He was an early protégé of Richard Murray (BS ’85), now the Thomas E. and Doris Everhart Professor of Control and Dynamical Systems and Bioengineering and William K. Bowes Jr. Leadership Chair in the Division of Biology and Biological Engineering. In Murray’s research group, Behnken found a close group of lab mates and a mentor who largely treated him as an equal and instilled a worldview he has carried with him—even when that world is far below his feet.

“At Caltech, students have a healthy amount of cynicism,” he says. “They ask, ‘Is this true? And do I really understand why it’s true or false?’ If you’re going to eventually fly on a rocket ship into space, as I did, having healthy cynicism is probably in your best interest.”

2021 DISTINGUISHED ALUMNI AWARD RECIPIENT

Barbara Burger

(PhD ’87, Chemistry)

President of Technology Ventures and Vice President of Innovation, Chevron

For her long and extraordinary career as a business leader at Chevron, spanning roles in science and business, marketing, and investment; her contributions to advancements in the energy transition; and for her prominent role as a mentor and advocate for women in science and business.

Barbara Burger invests in the future. As president of Chevron Technology Ventures, the energy company’s venture capital firm, she seeks out emerging technologies to aid in the worldwide transition toward a lower carbon future and funds new, innovative companies with big ideas. “Transitioning to a lower carbon energy system is a big, gnarly problem, and if we get it wrong, some communities will be disadvantaged more than others,” she says. “When I’m done, hopefully we’ll have planted some seeds and established some good momentum.”

The nature of her role requires that Burger be up to speed on research at the frontiers of an array of disciplines. Fortunately, adaptability has always been her forte. After graduate school at Caltech under the mentorship of John Bercaw, now the Centennial Professor of Chemistry, Emeritus, Burger joined Chevron as a research chemist. Later, she happened upon an internal posting for a technical specialist in aviation and, although she did not have direct experience in aerospace engineering, secured the job.

Burger credits her Caltech education for the confidence and courage to try new things. “I always say, ‘If I have all the experience you’re looking for, why do I want the job?’” she notes. “I’m at my best when I’m learning. I have such breadth in my career because I haven’t been afraid to go into places where I don’t know everything.”

Perhaps her biggest investment in the future is through her support of Caltech women who are interested in making their way down the less-well-traveled career path, as she did. To make that possible, in 2019 Burger endowed a set of resources at the Institute that includes a fellowship for doctoral students in chemistry who aspire to careers outside the academy.

“I’m a big believer in catalysts,” she says. “You want somebody who has a lot of potential to get that little catalyst to help them get started.”

The more that current and future students can glean from Burger’s generosity and counsel, the more extraordinary minds there will be to confront society’s challenges. Especially the biggest, gnarliest ones.

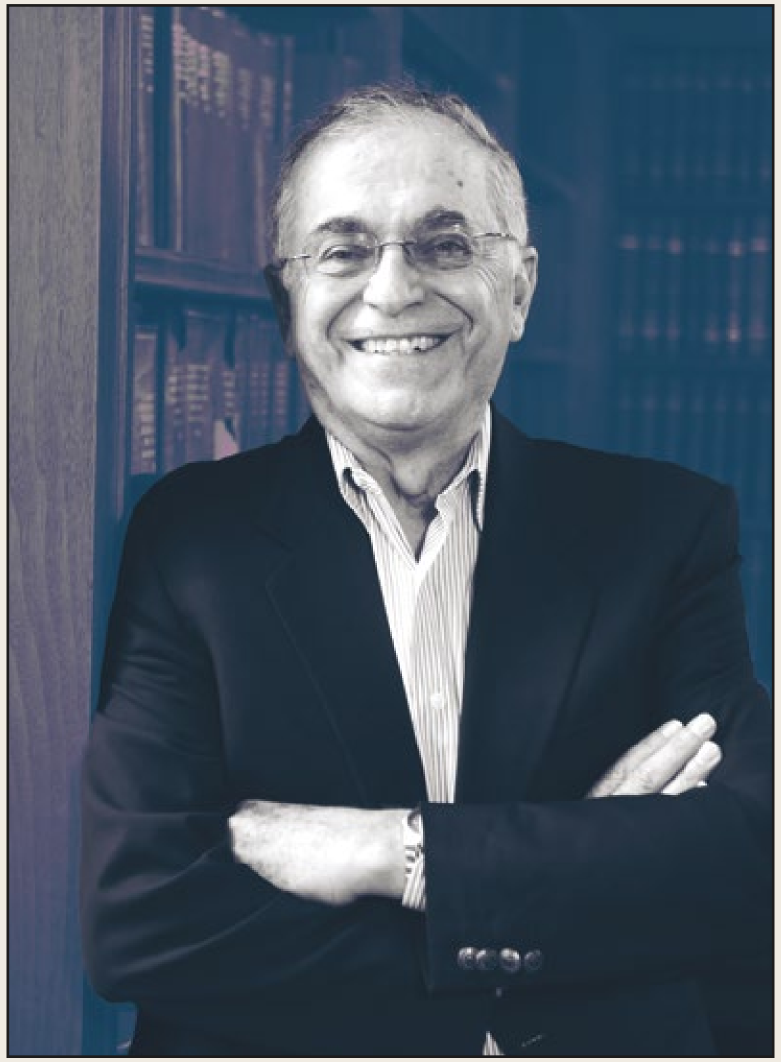
2021 DISTINGUISHED ALUMNI AWARD RECIPIENT

Charles Elachi

(MS ’69, PhD ’71, Electrical Engineering)

Professor Emeritus of Electrical Engineering and Planetary Science, Caltech

For his distinguished leadership in space exploration and planetary science as the longtime director of the Jet Propulsion Laboratory (JPL), where he was instrumental to realizing missions across the solar system including our own planet Earth, and for his many contributions helping to map out NASA’s long-term scientific future.



In 45 years at JPL, which Caltech manages for NASA, Charles Elachi innovated crucial spaceflight technologies and oversaw missions that landed rovers on Mars. But spaceflight was not what initially drew him to Southern California.

“I decided to come to Caltech not because it was the best school in the world, but because it’s near Hollywood,” Elachi laughs. “Fortunately, it’s also the best school in the world.”

Elachi joined JPL in 1970, while working on his PhD at Caltech, and achieved early-career success when a radar system he developed was chosen as the first experiment on the space shuttle *Columbia*’s second flight, in 1981. The instrument produced rich data not only for earth science but also for archaeology, penetrating meters into the sands of Egypt from space in order to reveal ancient, undiscovered drainage channels. The results were featured on the front cover of *Science* and reported in *National Geographic.*

After he was named JPL director in 2001, Elachi sought to imbue the lab’s activities with the intrepid spirit of Theodore Roosevelt, adopting his axiom “Dare mighty things” as JPL’s motto. Those mighty things included landing three rovers on Mars; launching powerful space telescopes to examine distant stars, black holes, and exoplanets; and sending into orbit satellites to probe Earth’s gravity, ocean, and climate systems.

According to Elachi, a pioneering spirit and the willingness to face down failure are key to JPL’s success. And he practiced what he preached. After attending a 2013 talk in San Francisco by an expert on drones, Elachi wondered: Could JPL fly a drone on Mars? After eight years of work by inventive, persistent engineers who brought this idea to life, the *Ingenuity* helicopter successfully flew on the Red Planet in 2021.

“I used to tell people, ‘The wilder it is, the more interested we are in the idea,’” Elachi says. “Maybe only one out of 10 ideas works. But that’s fine. That’s how you open new horizons.”

2021 DISTINGUISHED ALUMNI AWARD RECIPIENT

Laurie Leshin

(MS ’89, PhD ’95, Geochemistry)

President, Worcester Polytechnic Institute (WPI)

For her barrier-breaking leadership at universities such as Worcester Polytechnic Institute, which has been recognized for both teaching and research excellence and essential strides in diversity, equity, and inclusion under her guidance as the first woman to serve as president; and for her accomplishments as a distinguished geochemist and space scientist.

Since Laurie Leshin became WPI’s first female president in 2014, she has worked to amplify the school’s longtime focus on project-based learning. During her tenure, student participation has grown from 60 to 90 percent in the Global Projects Program, which connects diverse teams of undergraduates and faculty mentors with project centers across six continents, allowing them to work on challenges such as improving STEM education in Ghana, sanitation in Thailand, and public transportation in Russia.

“When I first joined WPI I thought ‘That’s the secret sauce,’” she says. “It’s almost a moral imperative that we scale the program up.”

Leshin has also prioritized diversity, equity, and inclusion. The school has one of the highest percentages of female undergraduates among STEM institutions, and the National Institutes of Health recently honored the university for enhancing faculty gender diversity. Although proud, Leshin notes there remains much to be done, especially to bring underrepresented people of color into STEM. With the world facing manifest difficulties, a waste of potential is a detriment to all. “There are thorny problems, whether it’s climate change or global health, food security or cybersecurity,” she says. “We need all the brains we can get working on this stuff.”

Leshin herself embraced big scientific challenges at a young age. As a 10-year-old, she saw the Viking landers’ pictures from the surface of Mars and was inspired by the similarity of the arid scenery to that of her home in Arizona. Just a few years later, Leshin was a NASA intern working on newer missions of that very same Viking program. She would return in 2005 as deputy director of NASA’s Exploration Systems Mission Directorate. She also served on the Mars Science Laboratory Science Team that analyzed data collected by the *Curiosity* rover at the Jet Propulsion Laboratory, which Caltech manages for NASA. Even after Leshin became a dean at Rensselaer Polytechnic Institute in 2011, an overlap with the Mars Science Laboratory’s calendar saw her split her time between two worlds.

As a WPI colleague pointed out, Leshin has approached all these challenges with a Caltech mindset: propose a hypothesis, test the idea, and apply the lessons to make a decision and move forward. “It has much to do with my Caltech training,” Leshin says. “It becomes your lens on the world.”

HOW WATER WORKS

(And Why It Matters)

Caltech scientists and engineers on campus and at JPL, which Caltech manages for NASA, use satellites and seismic monitors to track the planet's most important resource—water—and build miniature river systems in the lab to expand society's understanding of the water cycle amid climate change, droughts, and wildfires.

by Ker Than

This past July, the news was awash in reports of European towns and villages devastated by a cataclysmic flood. The raging waters enveloped homes, uprooted trees, and turned roadways into rivers of mud and debris. As he watched the images from his home in Pasadena, Christian Frankenberg spotted familiar places from his childhood. He grew up near the German city of Bonn, about a dozen miles from the Ahr Valley, a lush wine-making region that suffered some of the worst flood damage.

"I hiked the area quite a few times as a kid, so it literally struck home for me," says Frankenberg, who holds a joint appointment as a professor of environmental science and engineering and a JPL research scientist. "It's a narrow little valley, so it's always been prone to floods, but not to this degree. The water level was something like two meters higher than the previous highest water level. I thought, 'This is crazy.'"

Frankenberg absorbed the news of the floods with dismay but little surprise. After all, he researches how Earth's global carbon cycle interacts with and is influenced by its water cycle, the path water follows as it moves between the ocean, land, and atmosphere. This work helps to demonstrate how the frequency of extreme weather events is increasing because of climate change. As floods grow heavier and hurricanes stronger in some areas, droughts worsen in others, a portent of freshwater scarcity becoming one of the defining issues of the 21st century.

Graduate student Nathan Jones (left) and Ruby Fu, assistant professor of mechanical and civil engineering (right), use dye to analyze the fluid dynamics of water as it flows through lab-created snow.

Frankenberg tries not to be too affected by climate news, but scientific objectivity can be elusive when floodwaters drown your childhood playground or when your home state wages a continuous battle against wildfires exacerbated by chronic drought conditions and water shortages. Across Caltech, campus and JPL scientists and engineers who measure and monitor the planet's water find themselves in a similar place.

Mark Simons, the John W. and Herberta M. Miles Professor of Geophysics and JPL's chief scientist, and his team have used satellite radar to track how the ground in Southern California rises and falls like a breathing giant as water is pumped into and out of aquifers. "My primary interest was understanding what makes earth move across different time scales and the underlying mechanics that control this movement," he says. "But this is an example where what I know how to do can potentially be useful to society."

Spurred by curiosity and a fresh sense of urgency, researchers from the Institute's divisions, including JPL, and from interdisciplinary endeavors such as the Resnick Sustainability Institute (RSI) use every tool at their disposal to study and track Earth's water and to understand the vast energies and materials that water conveys. Their research draws on satellites in space and optical fibers deep underground, on advanced computer simulations and miniature, lab-built rivers. Their findings are filling gaps in our knowledge of Earth's hydrological cycle and improving the management of our most precious resource.

Their discoveries might also help prepare us for the tumultuous decades to come.

Coupled Cycles

Water is a primary factor that affects the extreme weather events connected to climate change. "It's seen as one of the dominant drivers of global warming in the future," Frankenberg says. "Ideally, with new climate models we can produce better statistical estimates for how extreme events might change in the future."

Frankenberg is helping to build one of those next-generation climate simulations through his work with the Climate Modeling Alliance (CliMA), which includes scientists, engineers, and mathematicians from campus, JPL, MIT, and the Naval Postgraduate School. CliMA aims to construct a new kind of model of Earth's land, oceans, and atmosphere that uses space- and ground-based planetary observations to predict droughts, heat waves, and extreme rainfall events more accurately than ever before.

The CliMA group's work demonstrates why accurate climate forecasts require a deep understanding of how climate change affects the water cycle and vice versa. For example, changes to the water cycle can drive changes to cloud cover in the atmosphere and snow cover on the ground, both of which affect Earth's albedo, or surface reflectivity. Higher albedo means more solar radiation is reflected into space, which helps cool the planet.

The connectedness of the global carbon and water cycles is another part of this research. In March, Frankenberg and former Caltech postdoctoral scholar Vincent Humphrey published a paper in *Nature* showing how the amount of water present in soil affects surface temperature and humidity, which in turn affect plants' ability to absorb carbon dioxide emissions.

"Here we have a smoking gun," says Humphrey of the finding. "We can say with confidence that soil moisture plays a dominant role in the year-to-year change we see in the amount of carbon taken up by the land."

Modeling Snowmelt

Every summer, the snow that has accumulated atop California's Sierra Nevada mountains during the winter slowly melts. Water trickles into streams, rivers, and reservoirs to irrigate farms in the state's fertile Central Valley, where much of the nation's fruit, nuts, and vegetables are grown, and to provide drinking water for millions of people from the San Francisco Bay Area to Southern California.

This same alpine process occurs around the world to provide water for billions of people. Yet science's picture of snowmelt is incomplete.

"A lot of the snow science that has been done is about observing snow from space," says Ruby Fu, an assistant professor of mechanical and civil engineering. "But that only gives you a 2-D picture. It's really challenging to monitor the depth of snow from space, but that depth is the dimension where a significant part of the snowpack hydrology takes place."

In 2013, JPL launched an airborne mission to fly remote-sensor-equipped airplanes over the Sierra Nevada to measure how much water the mountains hold and provide these data to water managers. The project was so successful that it has been spun off into its own company, Airborne Snow Observatories. Now Fu's team wants to address the same problem at a more fundamental level. "I'm looking at snowpack physics and trying to understand how snow in the Sierra Nevada melts and how it contributes to our hydrological systems in California," she says.

To accomplish this, Fu's group will create a miniature snowpack in the lab and then study it as it melts. "It's one of the craziest things I've ever decided to do," Fu says. A simple version of the experiment would be to substitute a block of ice for snow, but as Fu explains, "a block of ice melting is like caramel melting in your mouth. It's different than watching a snowpack melting, because a block of ice is not porous the way snow is."

Instead, she plans to create individual icy particles and have them accumulate into a pile of snow-like structures that can more accurately represent what happens when meltwater percolates through a snowpack and alters the snow structure in the process.

"I thought that it would be really useful if we could recreate a snowpack in the lab and actually watch it melt and then model the melting process," Fu says. "A better predictive model of how a snowpack becomes water could lead to better real-time water control by water managers, who need to know how much meltwater to expect."

Artificial Rivers

Fu is not the only one working to create natural environments in the lab. In a 4,000-square-foot warehouse called the Caltech Earth Surface Dynamics Laboratory, also known as the Flume Lab, located in the southwest part of campus, a model river flows toward a miniature ocean. Sediments carried by the water settle along the river's bottom and are deposited at its mouth to form a familiar fan-shaped delta. But whereas a real delta might take hundreds of years to form, this one begins to appear in months.

This is hydrology in miniature. The artificial delta spans only a meter or two at its widest point, and the tiny river that feeds it measures about 15 centimeters wide, 1 centimeter deep, and 5 to 6 meters long. The entire river system has been meticulously crafted by Professor of Geology Mike Lamb and his group inside the Flume Lab. "We have flumes similar to what you might have seen at science museums, where you can play with water and sediments, but at a more sophisticated level," he says.

Lamb's bespoke waterway allows his group to watch a delta develop more quickly, but the process still requires six months or more. "Although we can speed up time, we can't speed it up too much because we're trying to study the physics of how water flows and how sediments move in these systems. If we make it go too fast, we start to violate the conditions that occur in nature," he says.

Lamb's group employs these artificial water channels to study processes such as when a river changes its path, called an avulsion. A river avulsion usually occurs when an accumulation of sediment raises the riverbed relative to the neighboring land, making the river unstable. "Our artificial deltas display similar behaviors to what we see in nature," Lamb says. "A river channel will be going in one direction out to the ocean but eventually becomes unstable and jumps course. That is an avulsion."

Professor of Geology Mike Lamb oversees work in the Caltech Earth Surface Dynamics Laboratory, where his team builds artificial rivers to simulate natural processes.

It is crucial to understand avulsions because these course corrections can be sudden and violent, triggering catastrophic floods like the 1887 Yellow River flood and the 1931 China floods, which are estimated to have killed a combined 6 million people. By modeling avulsions in the lab, Lamb hopes to understand how they happen, where they might occur next, and how they might be affected by climate change.

For example, one of the group's latest experiments, detailed last summer in the journal *Proceedings of the National Academy of Sciences*, examined how river avulsions are impacted by a rising sea level. "Theories predict that the frequency of avulsions will increase with rising sea level and that avulsion locations will shift upstream under certain conditions," Lamb explains. "Those results bear out in our experiment, so it gives us some confidence that our computer models are getting the physics right."

Lamb also works on real-world deltas as a co-investigator on JPL's Delta-X project, which uses the Mississippi River Delta as a natural laboratory. Led by JPL scientist Marc Simard, Delta-X combines airborne remote sensing with on-the-ground measurements to study the delta's water, vegetation, and sediment. Although the airborne instruments can see overall sediment concentration, they do not penetrate the water to see sediment close to the riverbed.

That is where Lamb's team comes in. "We're ground-truthing. We're going out in a boat and measuring water and sediment fluxes and comparing that to the remote-sensing data," he says.

The goal of this research is to predict how the Mississippi River Delta will respond to a rising sea level, to find out which areas are most vulnerable to storms, and to forecast which parts of the delta will grow or disappear. "The Mississippi River wasn't dug by a bulldozer," Lamb says. "It has a certain size and depth, and it meanders and bends its way across the landscape, and much of that is determined by how the water moves sediment and where the sediment ends up."

Data Deluge

The story of the 21st century in the American West has become a story of drought. The past 20 years were the driest 20-year period since the 1500s in the region spanning Oregon to Mexico in the north-south direction and California to Colorado from west to east. A severe dry spell in the early 2000s was followed by record-breaking droughts in 2012 and 2016. The West is mired in drought again this year, and each new year brings the possibility of an extreme wildfire season worsened by the lack of rainfall.

Caltech postdoctoral scholar Gerard Salter retrieves a water sampler from the Wax Lake Delta while Caltech graduate student Justin Nghiem (MS '21) readies the sample bag. Samples are analyzed for suspended mineral sediment and particulate carbon to predict land loss in the Mississippi Delta region as part of the JPL-led Delta-X project.

"Over the course of studying these droughts, NASA realized two things: that we can really get a good handle on what's happening from space, and that this is the beginning of something bigger," says JT Reager, a research scientist in JPL's Surface Hydrology Group.

During these recent decades, NASA scientists were among those who demonstrated that the same factors that alter Earth's atmosphere also change its water cycle. The agency has responded to this information by launching an array of satellites that now form the backbone of science's ability to track the planet's water.

"We have more information streaming in now on water than we've ever had at any point in human history," Reager says. "NASA has several satellites up and several more that are going to be launching in the next five to 10 years." This includes a mission to study and track rain and snowfall, surface waters, and drought. "JPL has an observation of almost every component and every flux of the hydrological cycle," Reager says.

NASA generates so much data about water that it has become a major challenge to integrate the many streams of information into a single tributary from which to draw useful and actionable insights. "That's what we do all day: think of ways to connect different data sets," Reager says. He collaborates with Fu and others on campus on a project that uses data science and machine learning to seamlessly combine different data sets, whether they are gathered by satellites, airplanes, or boats.

In the future, some of that data could come from surprising places. For example, Assistant Professor of Geophysics Zhongwen Zhan (MS '08, PhD '13) aims to study water using underground optical fibers originally laid down for communications and which he previously used to study earthquakes. Zhan's team will use a new technology called distributed acoustic sensing (DAS) to monitor groundwater beneath Owens Lake in California, a mostly dry lake that the state hopes to revive by refilling the groundwater basin beneath it. DAS will convert fiber-optic cables around the lake into sensitive seismic arrays that scientists can use to measure the injection, withdrawal, and movement of groundwater under the lake.

"We want to see if we can basically throw all that data into a cauldron and try to understand some critical questions," says Simons. "For example, how can scientists direct and track water that has been reinjected into the ground? Can we improve our understanding of the interactions between ground and surface waters so we can learn how to best replenish underground reservoirs?

A World of Water

Both efforts to combine different water data sets—the DAS monitoring project and Fu's snowpack research—are funded by seed grants from RSI, which advances global sustainability through transformational science, engineering, and education. "RSI is interested in understanding the basic science and engineering that can help us progress to a more sustainable society, and it's clear that one aspect of sustainability is access to fresh water for drinking, agriculture, and other uses," says Simons, who leads RSI's Water Resources initiative.

A geophysicist by training, Simons followed a meandering path to study water. "When we look at these measurements of Earth, it's inescapable that the dominant signal sometimes is not tectonics but hydrology," he says.

Simons now seeks to adapt technologies he has used to study earthquakes and other seismic events to his investigation of water. For a 2018 study, for instance, his team used a satellite radar technology called interferometric synthetic aperture radar (InSAR) to track terrain changes across the Los Angeles Basin and the Santa Ana Coastal Basin that were caused by pumping water out of the ground. His team now uses the same technology to look at terrain changes caused by groundwater pumping in the San Gabriel Valley, where campus and Lab reside. The data will be shared with local water agencies to help them better understand their aquifers.

"We're not water managers," Simons says. "All we can say is, 'Here are some observations about your water resources. Now take this and fold it into your decision-making process.'"

Simons sees even more opportunities for research efforts from campus and Lab to inform how water is managed and monitored around the world. "If we can help people in developing nations better understand their aquifers, that's just as important as what we're doing in a place like California, where there are a vast number of other resources that can be used to understand the aquifer system," he adds. "My hope, and my intent, is that we take a global perspective to addressing these challenges in sustainability." [C]

Dive Deeper:
Conversations on Sustainability: Monitoring Water Resources from Space
with JPL's **JT Reager** and **Indrani Graczyk**

Watch the webinar at:
scienceexchange.caltech.edu/sustainabilityconversations

The Art of Predicting Tastes in Art

by Whitney Clavin

The thick brush strokes and soft color palettes of a Monet. The bold colors and abstract shapes of a Rothko. A new Caltech study, which appeared in the journal *Nature Human Behaviour* in May, shows that a simple computer program can accurately predict which paintings a person will like.

The study enlisted more than 1,500 volunteers through Amazon's crowdsourcing platform Mechanical Turk to rate paintings in the genres of impressionism, cubism, abstract, and color field. The volunteers' answers were fed into a computer program which, after this training period, could predict the volunteers' art preferences much better than would happen by chance.

"I used to think the evaluation of art was personal and subjective, so I was surprised by this result," says lead author Kiyohito Iigaya, a postdoctoral scholar in the laboratory of Fletcher Jones Professor of Psychology John O'Doherty, an affiliated member of the Tianqiao and Chrissy Chen Institute for Neuroscience at Caltech.

"The main point is that we are gaining an insight into the mechanism that people use to make aesthetic judgments," says O'Doherty.

In the study, the team programmed the computer to break a painting's visual attributes down into what they called low-level features—traits like contrast, saturation, and hue—as well as high-level features, which require human judgment and include traits such as whether the painting is dynamic or still.

"The computer program then estimates how much a specific feature is taken into account when making a decision about how much to like a particular piece of art," explains Iigaya. "Once the computer has estimated that, then it can successfully predict a person's liking for another previously unseen piece of art."

The researchers discovered that the volunteers tended to cluster into three general categories: those who like paintings with real-life objects, such as an impressionist painting; those who like colorful abstract paintings, such as a Rothko; and those who like complex paintings, such as Picasso's cubist portraits. The majority of people fell into the "real-life object" category.

The researchers found that they could also train a deep convolutional neural network (DCNN), a type of machine-learning program, to how to predict the volunteer's art preferences with a similar level of accuracy. In this case, the deep-learning approach did not include any of the selected low- or high-level visual features used in the first part of the study, so the computer had to "decide" what features to analyze on its own.

"In deep-neural-network models, we do not actually know exactly how the network is solving a particular task because the models learn by themselves much like real brains do," explains Iigaya.

In another part of the study, the researchers demonstrated that their simple computer program, which had already been trained on art preferences, could accurately predict which photos volunteers would like. [C]

The study, "Aesthetic preference for art can be predicted from a mixture of low- and high-level visual features," was funded by the National Institute of Mental Health (through Caltech's Conte Center for the Neurobiology of Social Decision Making), the National Institute on Drug Abuse, the Japan Society for Promotion of Science, the Swartz Foundation, the Suntory Foundation, and the William H. and Helen Lang Summer Undergraduate Research Fellowship. Other Caltech authors include Sanghyun Yi, Iman A. Wahle (BS '20), and Koranis Tanwisuth, who is now a graduate student at UC Berkeley.

Area Broken by Perpendiculars
Joseph Schillinger, 1934

Seconnet Point, Rhode Island
Worthington Whittredge,1880

IS SPACE PIXELATED?

The search for signatures of quantum gravity forges ahead

By Whitney Clavin

Sand dunes seen from afar seem smooth and unwrinkled, like silk sheets spread across the desert. But a closer inspection reveals much more. As you approach the dunes, you may notice ripples in the sand. Touch the surface and you would find individual grains. The same is true for digital images: zoom far enough into an apparently perfect portrait and you will discover the distinct pixels that make the picture.

The universe itself may be similarly pixelated. Scientists such as Rana Adhikari, professor of physics at Caltech, think the space we live in may not be perfectly smooth but rather made of incredibly small discrete units. "A spacetime pixel is so small that if you were to enlarge things so that it becomes the size of a grain of sand, then atoms would be as large as galaxies," he says.

Adhikari and scientists around the world are on the hunt for this pixelation because it is a prediction of quantum gravity, one of the deepest physics mysteries of our time. Quantum gravity refers to a set of theories, including string theory, that seeks to unify the macroscopic world of gravity, governed by general relativity, with the microscopic world of quantum physics. At the core of the mystery is the question of whether gravity, and the spacetime it inhabits, can be "quantized," or broken down into individual components, a hallmark of the quantum world.

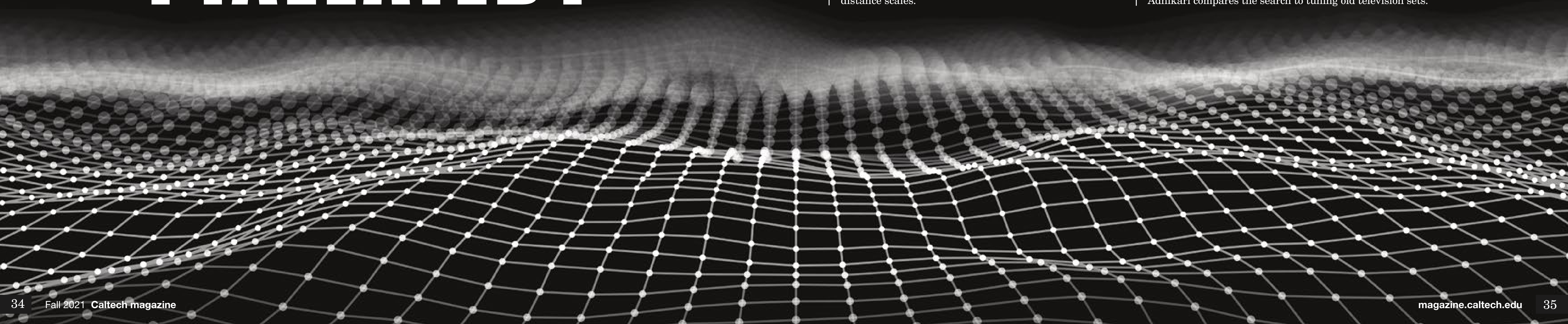
"Sometimes there is a misinterpretation in science communication that implies quantum mechanics and gravity are irreconcilable," says Cliff Cheung, Caltech professor of theoretical physics. "But we know from experiments that we can do quantum mechanics on this planet, which has gravity, so clearly they are consistent. The problems come up when you ask subtle questions about black holes or try to merge the theories at very short distance scales."

Because of the incredibly small scales in question, some scientists have deemed finding evidence of quantum gravity in the foreseeable future to be an impossible task. Although researchers have come up with ideas for how they might find clues to its existence—around black holes; in the early universe; or even using LIGO, the National Science Foundation-funded observatories that detect gravitational waves—no one has yet turned up any hints of quantum gravity in nature.

Professor of Theoretical Physics Kathryn Zurek would like to change that. She recently formed a new multi-institutional collaboration, funded by the Heising-Simons Foundation, to think about how to observe signatures of quantum gravity. The project, called Quantum gRavity and Its Observational Signatures (QuRIOS), unites string theorists, who are familiar with the formal tools of quantum gravity but have little practice designing experiments, with particle theorists and model-builders who are experienced with experiments but not working with quantum gravity.

"The idea that you might be able to look for observable features of quantum gravity is very far from the mainstream," she says. "But we'll be lost in the desert if we don't start focusing on ways to link quantum gravity with the natural world that we live in. Having observational signatures to think about tethers us theorists together and helps us make progress on new kinds of questions."

As part of Zurek's collaboration, she will work with Adhikari, an experimentalist, to develop a new experiment that uses tabletop instruments. The proposed experiment, called Gravity from Quantum Entanglement of Space-Time (GQuEST), will be able to detect not individual spacetime pixels themselves, but rather connections between the pixels that give rise to observable signatures. Adhikari compares the search to tuning old television sets.



Hirosi Ooguri has developed key mathematical tools for understanding string theory.

"When I was growing up, we could not get NBC, and we would try to tune around to get it. But most of the time, we would see the pixelated snow. Some of that snow we know is coming from the cosmic microwave background, or the birth of the universe, but if you tuned just off the peak of that, you could find snow from solar storms and other signals. That's what we are trying to do: to carefully tune in to the snow, or fluctuations of spacetime. We will be looking to see if the snow fluctuates in ways that align with our models of quantum gravity. Our idea could be bogus, but we have to try."

A new blueprint for the universe

Cracking the problem of quantum gravity would be one of the greatest achievements of physics, on par with the two theories that researchers want to merge. Albert Einstein's general theory of relativity reshaped the view of the universe, showing that space and time can be thought of as one continuous unit, spacetime, which curves in response to matter. Gravity, the theory explains, is nothing more than the curvature of spacetime.

The second theory, quantum mechanics, describes the three other known forces in the universe aside from gravity: electromagnetism, the weak nuclear force, and the strong nuclear force. A defining feature of quantum mechanics is that these forces can be quantized down to discrete packets, or particles. For example, the quantization of the electromagnetic force results in a particle known as the photon, which makes up light. The photon works behind the scenes at microscopic scales to transmit the force of electromagnetism. Though the electromagnetic field appears continuous at the large scales we are used to, it becomes "bumpy" with photons when you zoom in.

The central question of quantum gravity, then, is this: does spacetime also become a frothy sea of particles at the smallest scales, or does it remain smooth like the surface of an unbroken lake? Scientists generally believe that gravity should be bumpy at the smallest scales; the bumps are hypothetical particles called gravitons. But when physicists use mathematical tools to describe how gravity might arise from gravitons at very tiny scales, things break down.

"The math become impossible and produces absurd answers such as infinity where we should get finite numbers as answers. It implies something is amiss," says Hirosi Ooguri, the Fred Kavli Professor of Theoretical Physics and Mathematics and director of the Walter Burke Institute for Theoretical Physics. "It is not well appreciated how hard it is to build a consistent theoretical framework, to unify general relativity and quantum mechanics.

"It would seem to be impossible, but then we have string theory."

Strings at the bottom

Many scientists would agree that string theory is the most complete and probable theory of quantum gravity to date. It describes a universe with 10 dimensions, six of which are squirreled away unseen while the remaining four make up space and time. True to its name, the theory postulates that all matter in the universe is, at the most fundamental level, made of teeny strings. Like a violin, the strings resonate at different frequencies or notes, with each note corresponding to a unique particle such as an electron or photon. One of these notes is thought to correspond to the graviton.

John Schwarz, the Harold Brown Professor of Theoretical Physics, Emeritus, was one of the first people to realize the power of string theory to bridge the gap between the quantum world and gravity. In the 1970s, he and his colleague Joël Scherk struggled to use the mathematical tools of string theory to describe the strong nuclear force. However, they realized the theory's disadvantages could be turned into advantages if they changed course.

"Instead of insisting on constructing a theory of the strong nuclear force, we took this beautiful theory and asked what it was good for," Schwarz said in a 2018 interview. "It turned out it was good for gravity. Neither of us had worked on gravity. It wasn't something we were especially interested in, but we realized that this theory, which was having trouble describing the strong nuclear force, gives rise to gravity. Once we realized this, I knew what I would be doing for the rest of my career."

It turns out that, compared with the other forces, gravity is an oddball. "Gravity is the weakest force we know of," explains Ooguri. "I'm standing here on the fourth floor of the Lauritsen building, and the reason gravity is not pulling me through the floor is that, inside the concrete, there are electrons and nuclei that are supporting me. So, the electric field is winning over the gravitational force."

However, while the strong nuclear force weakens at shorter and shorter distances, gravity becomes stronger.

"The strings help soften this high-energy behavior," Ooguri says. "The energy gets spread out in a string."

Tabletop tests of quantum gravity

The challenge with string theory lies not only in making it consistent with our everyday, low-energy world, but also in testing it. To see what occurs at the minuscule scales where spacetime is theorized to become grainy, experiments would need to probe distances on the order of what is known as the Planck length, or 10^{-35} meters. To reach such extreme scales, scientists would have to build an equally extreme detector. "One way to go is to make something the size of the solar system and look for signatures of quantum gravity that way," says Adhikari. "But that's really expensive and would take hundreds of years!"

Instead, Zurek says, researchers can investigate aspects of quantum gravity using much smaller experiments. "For the lower-energy experiments we are proposing, we don't need the whole machinery of string theory," she says. "Theoretical developments associated with string theory have provided us with some tools and a quantitative grasp on what we expect to be true in quantum gravity."

The experiments proposed by Zurek, Adhikari, and their colleagues focus on effects of quantum gravity that could be observed at more manageable scales of 10^{-18} meters. That is still very small, but potentially doable using very precise laboratory instruments.

These tabletop experiments would be like mini LIGOs: L-shaped interferometers that shoot two laser beams in perpendicular directions. The lasers bounce off mirrors and meet back in their place of origin. In LIGO's case, gravitational waves stretch and squeeze space, which affects the timing of when the lasers meet. The quantum-gravity experiment would look for a different kind of spacetime fluctuation consisting of gravitons that pop in and out of existence in what some call the quantum, or spacetime, foam. (Photons and other quantum particles also pop in and out of existence due to quantum fluctuations.)

Rather than look for the gravitons individually, the researchers seek "long-range correlations" between complicated collections of the hypothetical particles, which result in observable signatures. Zurek explains that these long-range connections are like larger ripples in the sea of spacetime as opposed to the frothy foam where individual particles reside.

Rana Adhikari (left) and Kathryn Zurek (right) have teamed up to develop a new tabletop experiment to look for "long-range correlations" between collections of gravitons.

"We think there are spacetime fluctuations that may perturb the light beams," she says. "We want to design an apparatus where spacetime fluctuations kick a photon out of the beam of the interferometer, and then we would use single-photon detectors to read out that spacetime perturbation."

Emergent spacetime

"Gravity is a hologram," says Monica Jinwoo Kang, a Sherman Fairchild Postdoctoral Fellow in Theoretical Physics at Caltech, when explaining the holographic principle, a key tenet of Zurek's model. This principle, which was realized using string theory in the 1990s, implies that phenomena in three dimensions, such as gravity, can emerge out of a flat two-dimensional surface.

"The holographic principle means that all the information in a volume of something is encoded on the surface," Kang explains.

More specifically, gravity and spacetime are thought to emerge from the entanglement of particles taking place on the 2-D surface. Entanglement occurs when subatomic particles are connected across space; the particles act as a single entity without being in direct contact with each other, somewhat like a flock of starlings. "Modern perspectives on quantum gravity inspired by string theory suggest that spacetime and gravity materialize out of networks of entanglement. In this way of thinking, spacetime itself is defined by how much something is entangled," says Kang.

In Zurek and Adhikari's proposed experiment, the idea would be to probe this 2-D surface, or what they call the "quantum horizon," for graviton fluctuations. Gravity and spacetime, they explain, emerge out of the quantum horizon. "Our experiment would measure the fuzziness of this surface," says Zurek.

That fuzziness would represent the pixelation of spacetime. If the experiment succeeds, it will help redefine our concept of gravity and space at the most fundamental, deepest levels.

"If I drop my coffee mug and it falls, I'd like to think that's gravity," says Adhikari. "But, in the same way that temperature is not 'real' but describes how a bunch of molecules are vibrating, spacetime might not be a real thing. We see flocks of birds and schools of fish undertake coherent motion in groups, but they are really made up of individual animals. We say that the group behavior is emergent. It may be that something that arises out of the pixelation of spacetime has just been given the name gravity because we don't yet understand what the guts of spacetime are." [C]

In Memoriam

Read more about their lives at **magazine.caltech.edu/post/in-memoriam**

David Grether
1938–2021

David Grether, the Frank Gilloon Professor of Economics, Emeritus, passed away on September 12. He was 82. Grether was trained in econometrics, a field that applies statistical methods to economic data to determine economic relationships. His research into individual decision-making helped develop what was then a new field, experimental economics, which examines economic questions through the use of experiments of auctions, games, and markets.

Felix H. Boehm
(MS '51, PhD '54)
1924–2021

Felix H. Boehm, the William L. Valentine Professor of Physics, Emeritus, and a pioneering nuclear physicist, passed away on May 25 at the age of 96. Boehm was among the first to use nuclear physics techniques to do fundamental research on weak interactions and the nature of neutrinos (nearly massless subatomic particles). He initiated the first experiment at a nuclear reactor to look for neutrino oscillations, spontaneous changes of a neutrino's "flavor."

Stephen D. Bechtel, Jr.
1925–2021

Stephen D. Bechtel, Jr., senior director of Bechtel Group Inc. and a life member of the Caltech community, passed away on March 15. He was 95 years old. In 1957, Bechtel founded the S. D. Bechtel, Jr. Foundation, which supports education and environmental programs in California. The construction of Caltech's 211-bed Bechtel Residence, which opened in 2018, was supported by that foundation and the building is named in Bechtel's honor.

Endnotes

In recognition of the *Break Through* campaign (see page 16), alumni were asked: What has been your most significant personal breakthrough?

Editor's Note: Because of a technical issue, we were unable to identify some of the people who responded to this question. If you replied, please send your name, graduation year, and hometown to ***magazine@caltech.edu*** *so we can include it in our online edition.*

My autism diagnosis. Regarding Caltech, it explained why I flamed: pressure and poor social knowledge. In retrospect, I realize that I was far from alone in being autistic. It also helps me understand my autistic son, who may very well go to Caltech.

My two juggling partners and I, performing as the Stanford Juggling Research Institute, won the silver medal in 2004 at the Teams Championships of the International Jugglers' Association's annual festival by presenting a scientific and professional yet funny club-passing routine.

Martin Frost (BS '69)
HALF MOON BAY, CA

Some years back, I took a timeout from my STEM career and went to Tibet. That bloomed into a 14-year career leading a nonprofit that ran programs in education, health care, job skills training, and cultural heritage preservation. I've always had a burning desire to write a book—not only to tell my own story but also to share what I learned about the place and its people. My book, *Compassion Mandala: The Odyssey of an American Charity in Contemporary Tibet*, was published in September 2020.

—Pamela Logan (BS '81, MS '82)
LAKEWOOD, CO

No big intellectual or business breakthroughs. Did first play water polo at Caltech and ended up in the USA Water Polo Hall of Fame. Bet that's a first for Tech.

Coincidentally, I have just published a book called *Breakthrough*! But seriously, overcoming the rejection everyone who tries to get published faces and becoming a full-time writer has been a significant breakthrough.

—Marcus Chown (MS '84)
LONDON, UK

My biggest breakthrough was completing the ME masters program while a single parent raising a 3-year-old daughter and a 4-year-old son. It wasn't easy.

My personal breakthrough was when I applied the knowledge and skills I gained at Caltech as a Chemical Engineering major to study, test for, and receive my Civil Engineering license.

—Alex Padilla (BS '07)
FOUNTAIN VALLEY, CA

Raising children is a challenge. My breakthrough was seeing my daughter, who is attending a college in the east, get accepted and participate in this summer's SURF program at Caltech.

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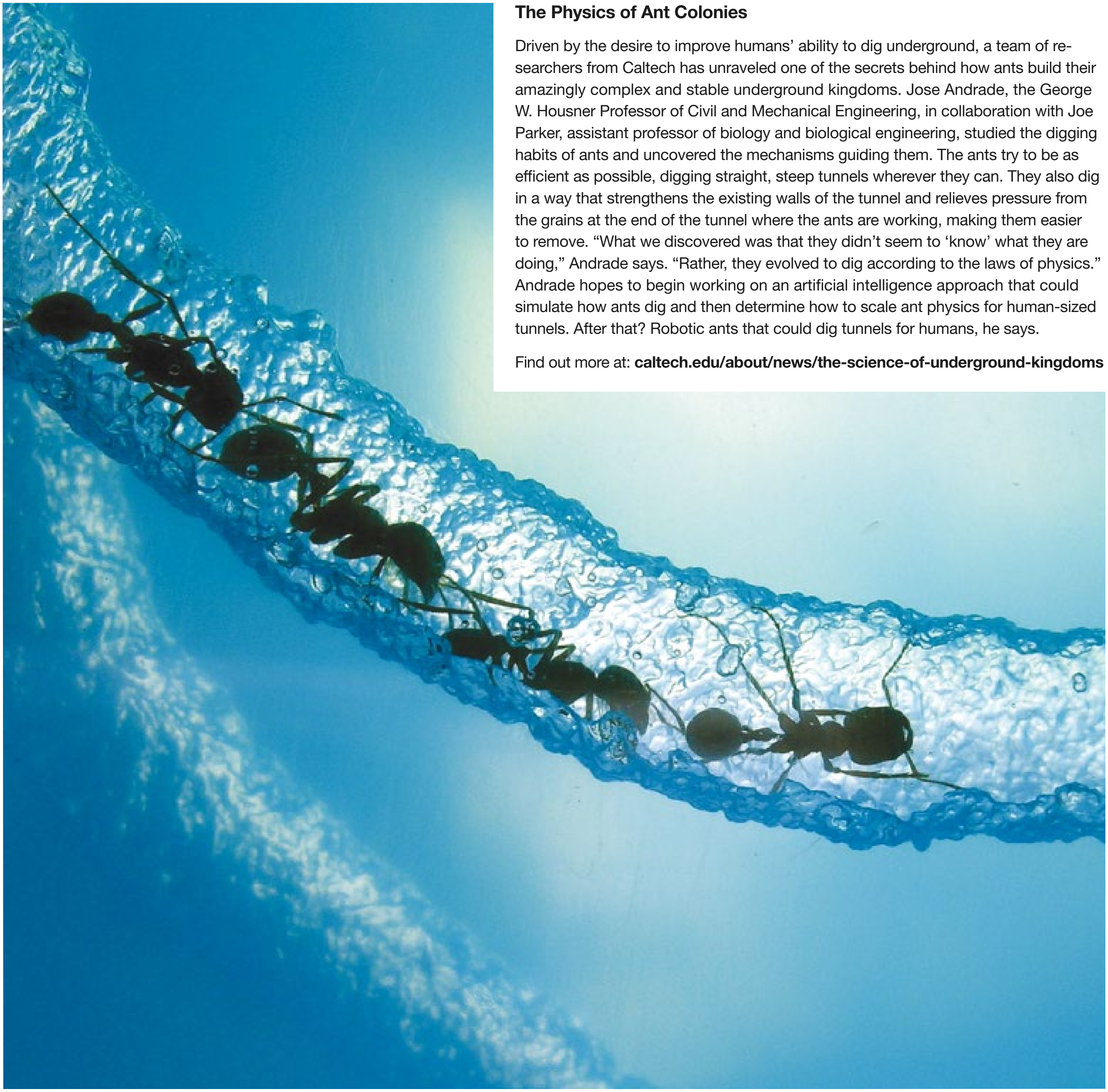

The Physics of Ant Colonies

Driven by the desire to improve humans' ability to dig underground, a team of researchers from Caltech has unraveled one of the secrets behind how ants build their amazingly complex and stable underground kingdoms. Jose Andrade, the George W. Housner Professor of Civil and Mechanical Engineering, in collaboration with Joe Parker, assistant professor of biology and biological engineering, studied the digging habits of ants and uncovered the mechanisms guiding them. The ants try to be as efficient as possible, digging straight, steep tunnels wherever they can. They also dig in a way that strengthens the existing walls of the tunnel and relieves pressure from the grains at the end of the tunnel where the ants are working, making them easier to remove. "What we discovered was that they didn't seem to 'know' what they are doing," Andrade says. "Rather, they evolved to dig according to the laws of physics." Andrade hopes to begin working on an artificial intelligence approach that could simulate how ants dig and then determine how to scale ant physics for human-sized tunnels. After that? Robotic ants that could dig tunnels for humans, he says.

Find out more at: **caltech.edu/about/news/the-science-of-underground-kingdoms**