Spring 2022

# Caltech magazine

What do jellyfish know?

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**Left:** Members of the classes of 2020 and 2021 assembled in person on October 16, 2021, to celebrate their commencement after previously holding virtual graduation gatherings during the COVID-19 pandemic. For more, see "Procession in Person" on **page 12.**

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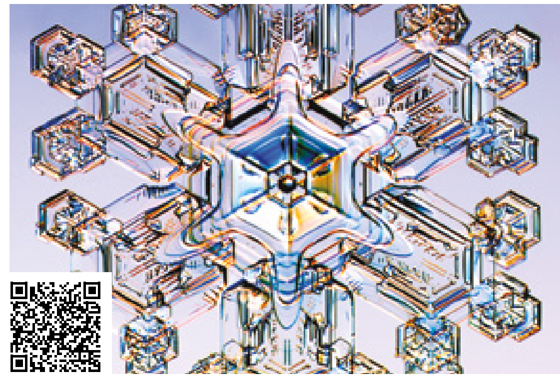

Research During a Pandemic
Photos: **Science marches on**

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# Letters

## Moment of "Gravity"

Just read your Quantum Gravity article. Phenomenal! Beautifully written, a great tour of Caltech physics.

**David Zierler**
Director, Caltech Heritage Project
*(see story on **page 15**)*

## Waste Water?

Very good story about extremely extensive research into our SoCal water situation. But no mention of dumping half our precious resource into the ocean for political reasons. We search to the heavens for reasons but ignore the obvious!

**George Cooke (BS '53)**

## Socially Aware

*A roundup of social media reactions to stories posted on **magazine.caltech.edu**.*

**… there's no one quite like Dr. Libbrecht!**

**Geoff Steeves** on Facebook
in response to a story featuring professor of physics and snowflake expert Ken Libbrecht (BS '80).

---

**So proud of you Mahider 🟥keep up the good work!!! 👇🏿👇🏿💟💟🟥🟥💏🏿**

**Gomez Maria** on Facebook
in response to a #SoCaltech profile on Mahider Gessesse.

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**Thank you, @Caltech @CaltechMagazine, for featuring my talk!**

**Lei Li** (PhD '19), postdoctoral scholar research associate in medical engineering, on Twitter in response to a story about his photoacoustic engineering research that included a video of his TED Talk.

---

**Sounds like something I'd say.**

**Joe Parker,** assistant professor of biology and biological engineering, on Twitter in response to a story on rove beetles featuring his quote: "They're the chemists of the animal kingdom."

---

**The chalkboard! I love it! One of my favorite places on the campus. Grateful that it exists and is maintained.**

**conrad773** on Instagram in response to a photo of **Rana Adhikari**, professor of physics; and **Kathryn Zurek**, professor of theoretical physics.

## For the Record

**The following individuals who responded to the Endnotes question in the Fall 2021 issue were not able to be identified due to a technical issue. In recognition of the *Break Through* Campaign, alumni were asked: "What has been your most significant personal breakthrough?"**

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

**Alvah T. Strickland (MS '65)**
HONOLULU, HI

My autism diagnosis. Regarding Caltech, it explained why I flamed out: 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.

**Chuck Coleman (MS '87)**
ALEXANDRIA, VA

*California Winters,* a painting by Pasadena resident Victoria Benitez, features the Caltech campus.

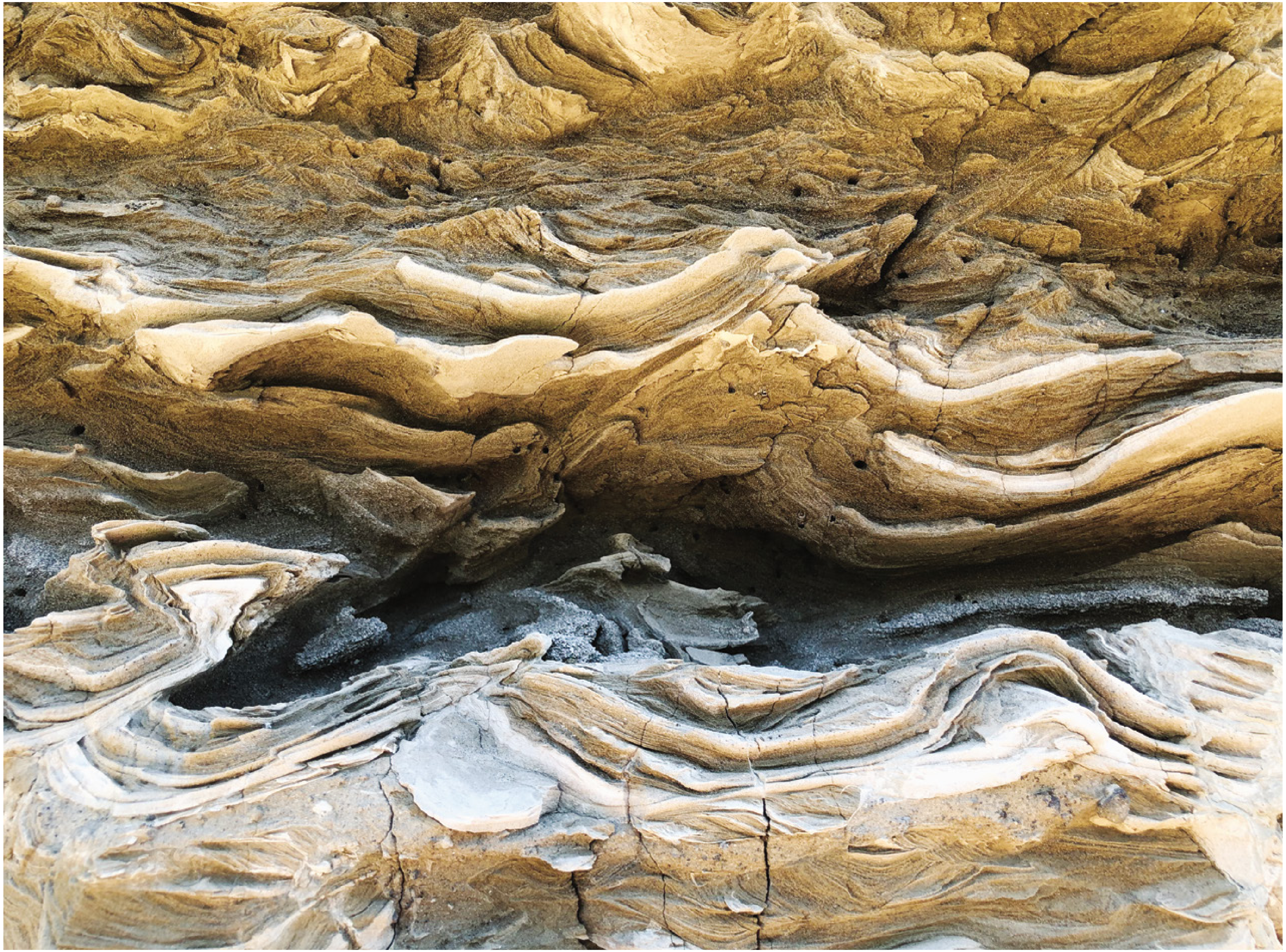
## Endnotes Sneak Peek

What are your fondest memories of Mead and/or your undergraduate chemistry classes there?

I was a TA for freshman chemistry lab in Mead in 1984–85. One day, one of the students suddenly called out, "I think I have a problem!" For reasons never made clear, he had leaned heavily on the distilled water spigot. His weight had pulled the spigot out of the pipe entirely! Distilled water was gushing out of the open pipe as he tried to block the flow with his hands, which made it spray everywhere. I started following the pipe back to its source. The pipe went to a main, which went across the ceiling and out of the lab room into the hallway and then down the hallway and out of the building into Noyes next door! I raced into Noyes to see if there was some place to shut the flow down inside. Someone from the stockroom there knew where it was and we got the water shut off, but not before we had created an enormous flood!

**James E. Hanson (PhD '90)**
MILLTOWN, NJ

**For more memories of the Clifford S. and Ruth A. Mead Memorial Undergraduate Chemistry Laboratory, see Endnotes on page 40.**



# SoCaltech

- Why economist Kirby Nielsen started writing haiku
- Meet Caltech's new board chair Dave Thompson (MS '78)
- A historic first for JPL
- Big quantum news; and more

## A Study in Sediments

The 2022 photo calendar produced by the Division of Geological and Planetary Sciences (GPS) features winning photographs from a division-wide photo contest. This selection, *Mono Lake Sediments From the Wilson Creek Formation, California*, shows sediment deposits in the lake. The description states: "During glacial times, when Sierra Nevada glaciers extended to their maximum glacial positions, and the lake was greatly elevated, icebergs floated in Lake Russell and deposited drop stones in the Wilson Creek Formation."

GPS research technician Mark Garcia captured this photo on June 20, 2021, while assisting with the International Geobiology training course, a five-week intensive summer program for PhD students and postdocs. At over 1 million years old, Mono Lake is one of the oldest in North America. Salts and minerals have washed into the lake, which has no outlet, from Eastern Sierra streams over time. The interaction of freshwater springs and alkaline lake water led to the formation of "tufa towers," calcium-carbonate spires and knobs notable for their unusual shapes and abundance. These towers have aided science's understanding of the climate history of this region.

"We arrived about two hours before the group of geobiology students," Garcia says of the day he took the photo. "Out of 12 photos I took, this one was my favorite."

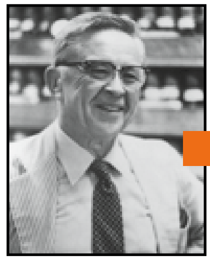
# New Names

The Caltech Board of Trustees, in accord with recommendations from President Thomas F. Rosenbaum, the Committee on Naming and Recognition, and the Ruddock House Renaming Committee, announced in November 2021 the names that would replace campus assets and honors that previously memorialized individuals affiliated with the eugenics movement:

**Caltech Hall** (formerly the Robert A. Millikan Memorial Library) recognizes past, present, and future generations of faculty, postdoctoral scholars, researchers, alumni, students, and staff who contribute to the Institute and to society.

**The Lee F. Browne Dining Hall** (formerly the Harry Chandler Dining Hall) is named in honor of Lee Franke Browne, a longtime educator who worked to address disparities within the country's educational systems. Browne was Caltech's director of secondary school relations for two decades beginning in the 1970s.

**The Judge Shirley Hufstedler Professorship** (formerly the Robert A. Millikan Professorship) is named in honor of Shirley Mount Hufstedler, the country's first cabinet-level secretary of education (as appointed by President Jimmy Carter), first female federal appellate judge, and a member of the Caltech Board of Trustees for 39 years.



**The Edward B. Lewis Professorships of Biology** (formerly the Albert Billings Ruddock Professorships of Biology) are named in honor of Caltech alumnus and longtime faculty member Edward B. Lewis (PhD '42), who dedicated his academic career to Caltech and was awarded a Nobel Prize in 1995 for his groundbreaking studies of how genes regulate the development of specific regions of the body.

**Grant D. Venerable House** (formerly Ruddock House) is named in honor of Grant Delbert Venerable (BS '32), the first Black student to graduate from Caltech. Venerable received his undergraduate degree in civil engineering and went on to work as a mining engineer, and to own and operate a hotel and an eraser manufacturing company.

Scan the QR code to see an updated version of the Caltech campus map.

## Caltech to Host Science Olympiad Tournament

The nation's brightest young scientific minds are gearing up for the 2022 Science Olympiad National Tournament, which will be hosted by Caltech on May 13 and 14, 2022. The competition and events will take place online because of the COVID-19 pandemic. Science Olympiad is the premier science competition for middle and high school students. More than 2,000 are expected to take part in the festivities, which will include an opening ceremony; a STEM Expo featuring panels, discussions, and webinars; as well as an awards ceremony on May 18. The theme for this year's competition is "Imagination." Caltech president Thomas F. Rosenbaum will speak at the opening ceremony, followed by a keynote address from Frances Arnold, Linus Pauling Professor of Chemical Engineering, Bioengineering and Biochemistry, and winner of the 2018 Nobel Prize for Chemistry.

**For more information, visit: scienceolympiad2022.com**

# Quantum Quantifying

The new Dr. Allen and Charlotte Ginsburg Center for Quantum Precision Measurement at Caltech will develop tools and concepts with the potential to influence all areas of science and technology through unprecedented sensing, measurement, and engineering capabilities.

As the fulcrum of a major initiative in quantum science and technology, the center will unite a diverse community of theorists and experimentalists devoted to understanding quantum systems and their potential uses. It will bring together researchers in three fields that progress hand in hand: quantum sensing; quantum information; and gravitational-wave detection, the direct observation of ripples in spacetime.

The center will be housed in a new six-story building to be constructed with the support of a donation by Dr. Allen and Charlotte Ginsburg. The new building will bring architectural innovation to a historic, central campus entrance on California Boulevard. It will feature four floors of airy interaction spaces and offices built atop two floors of state-of-the-art underground laboratories made possible through a grant from the Sherman Fairchild Foundation. The entire project is fully funded by philanthropy.

The subterranean labs will be named for Kip Thorne (BS '62), Caltech's Richard P. Feynman Professor of Theoretical Physics, Emeritus. Thorne is among three scientists who shared the 2017 Nobel Prize in Physics for their roles in developing LIGO (Laser Interferometer Gravitational-Wave Observatory).

**"In many ways, this feels like a homecoming. Some of the most impactful experiences of my career have taken place on the Caltech campus and at JPL—lessons learned and goals achieved that have shaped me as a leader and a space scientist. I will work every day to ensure that JPL is a place where all belong and thrive. We will dare mighty things, together."**

**—Laurie Leshin (MS '89, PhD '95),** *current president of the Worcester Polytechnic Institute, has been appointed director of JPL and vice president of Caltech. She will be the first woman to lead JPL in the Lab's history and will take on that role beginning May 16, 2022.*

# Science in 17 Syllables

Kirby Nielsen, assistant professor of economics, researches individuals' decision-making behavior and uses experiments to study human perception of risk and uncertainty. Her field of experimental economics explores how people make choices involving financial investments, health care, and managerial decisions in the workplace.

Nielsen has added a creative twist to her own workplace behavior. She writes haiku summaries of her research papers, a practice that, she says, helps her think about the most efficient way to describe and present her work. "It takes a lot of time and practice to convey an idea simply and succinctly. That got me thinking that the ultimate challenge would be to communicate the whole story of a paper in just a sentence or two. The haiku structure provides a fun avenue for this and lets me add a little bit of poetry into the science." Here are some of the fruits of her labor:

**The paper:**
**"Preferences for the Resolution of Uncertainty and the Timing of Information"**
(*Journal of Economic Theory*, September 2020)

**The haiku:**
**"If it has happened
you want to know it sooner.
Otherwise, you'll wait."**

**The paper:**
**"Timing of Communication"**
(with Puja Bhattacharya and Arjun Sengupta; *The Economic Journal*, August 2020)

**The haiku:**
**"Promises are good
but cooperation fades.
Reports are better."**

**The paper:**
**"Teams Promise But Do Not Deliver"**
(with Puja Bhattacharya, John Kagel, and Arjun Sengupta; *Games and Economic Behavior*, September 2019)

**The haiku:**
**"People will promise.
It makes them cooperate.
But don't trust a group!"**

Visit Nielsen's website at **kirbynielsen.com** to read more of her haiku.

## Alum-to-Alum

**"The joy of discovery is so huge. That's why we all got into it. And without minimizing the difficulties in science, it's important to constantly remind yourself of this because, if not, then the joy of science will go away. And if it goes away, then it's just not worth doing this job."**

**–Ardem Patapoutian (PhD '96)**

*Professor of Neuroscience, Scripps Research, and recipient of the 2021 Nobel Prize in Physiology or Medicine*

Visit:
**magazine.caltech.edu/ardem-patapoutian** to watch a video interview between Patapoutian and content and media strategist Lori Dajose (BS '15), in which they discuss his time at Caltech and the research that led to his groundbreaking discoveries of receptors for temperature and touch.

# Dave Thompson

## New Board of Trustees Chair

In 1976, Dave Thompson (MS '78), the new chair of Caltech's Board of Trustees, participated in a summer program at JPL, which Caltech manages for NASA. There, he helped with NASA's Viking Project, which successfully landed the first spacecraft on Mars.

"We would work according to Mars time, and that didn't always map to Earth time," says Thompson. "I can remember the excitement surrounding the first landing, which occurred around 4 in the morning. Of course, everybody was working all night beforehand."

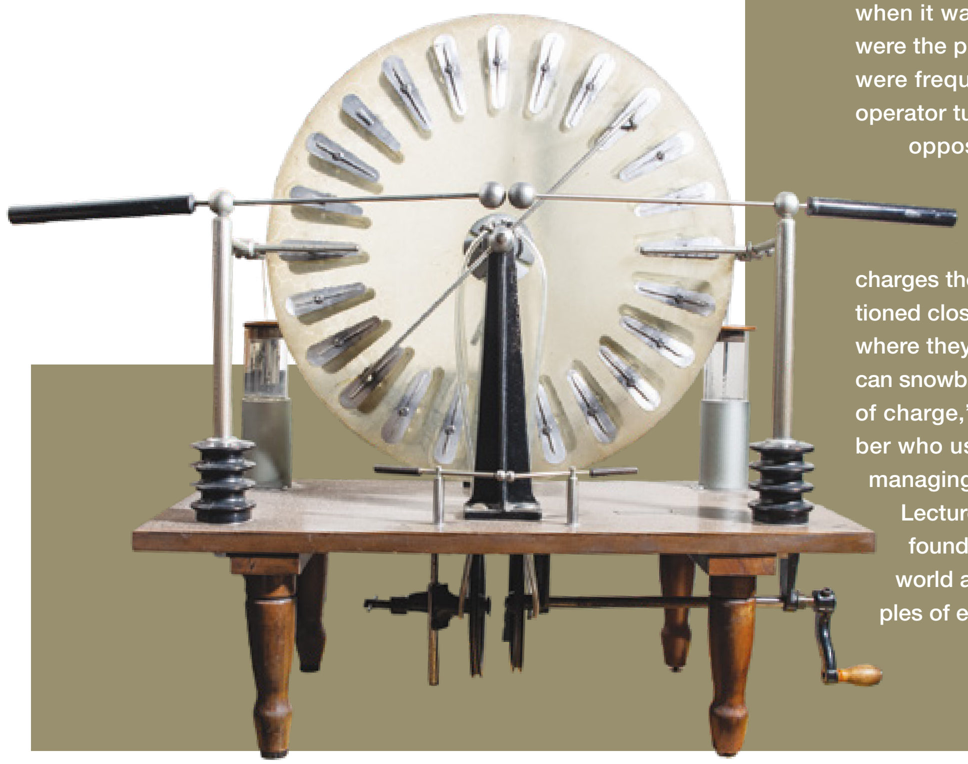
That was his introduction to the Institute, where, as a graduate student, he would pursue rocket propulsion and control under the guidance of adviser Bob Cannon and collaborator Homer Joseph Stewart (PhD '40), a co-founder of JPL. Thompson credits his Caltech education for helping to shape his entrepreneurial spirit. In 1982, he founded Virginia-based Orbital Sciences Corporation, a designer and manufacturer of space and rocket systems.

As he works with the Caltech Board to define priorities, Thompson sees opportunities to enhance the student experience, scale up research thrusts in areas of increasing focus, secure JPL's future beyond the next decade, and accelerate progress in diversity and inclusion throughout the Caltech community, including the Board of Trustees.

"I'd like to see us continue to support strong investment in our people—faculty, students, postdocs—and facilities, and continue the progress we've made in the last decade or so with fundraising from an expanded group of contributors, even beyond the almost 15,000 individuals who contributed to the *Break Through* campaign," says Thompson, who has been a Caltech trustee since 2012.

Thompson replaced David Lee (PhD '74), who joined the board in 2000 and was elected chair in 2012. Lee will remain on the board as a senior trustee and chair emeritus and as a member of multiple standing committees. Trustees Barbara Barrett and Ronald Linde (MS '62, PhD '64) were elected to serve as vice chairs.

## Object Lesson: The Wimshurst Machine



Developed in the 1880s by British inventor James Wimshurst, this spinning contraption generates the same kind of static electricity that makes your hair stand on end. In the era when it was invented, electrostatic machines of this sort were the primary means of generating high voltage and were frequently used to power X-ray tubes. When an operator turns the machine's crank, its two wheels spin in opposite directions. Small electrical charges on the discs are amplified and gathered in two jars, one for positive charges and the other for negative ones, placed on either side of the wheels. The charges then travel through rods to two metal balls positioned close to each other in front of the spinning wheels, where they are discharged as giant sparks. "This process can snowball, creating up to hundreds of thousands of volts of charge," explains Zach Tobin (MS '13), a staff member who uses this Wimshurst machine as part of his job managing physics demonstrations for Caltech's Feynman Lecture Hall. The machine can be found in classrooms around the world as a tool to teach the principles of electrostatics.

Watch a video about Zach Tobin and physics demonstrations:

## Newton Nguyen (fifth-year graduate student)

*#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.***

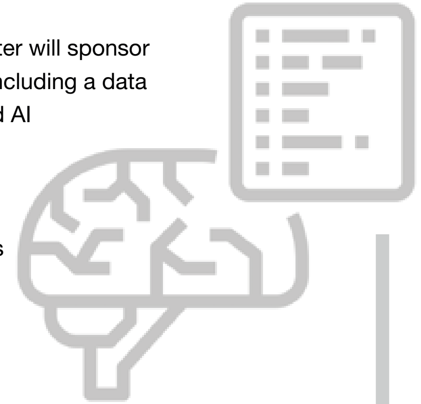
*Newton Nguyen (MS '19) is a fifth-year graduate student in environmental science and engineering. Through his research with Christian Frankenberg, a professor of environmental science and engineering and JPL research scientist, he aims to develop a new greenhouse gas observation network to monitor carbon emissions. Nguyen, who lost his eyesight at age 12 due to a degenerative vision condition, co-founded the Caltech Disability Coalition with Krystal Vasquez, a graduate student in chemistry. In his spare time, Nguyen runs marathons and competes in triathlons. He helped found the Caltech Triathlon Club and serves as its president.*

"I went to geophysics, then to climate science and math. It's a lot of visual data, but I generate the plots myself with my own code. I can listen to my computer read the code aloud and understand what's being typed out. There are three steps I use to understand the data. Number one is developing the code to actually generate the figures to look through the data. The second is looking through different statistical measures to understand what the data looks like, but that only gives you a coarse picture of what's going on. Third, I sit down with my adviser, collaborators, or even just other friends at Caltech and discuss the details in the figures. I learn insights that I didn't catch when they described the data to me. It took a year or two to figure it out, but it ended up working. In many ways, having to do all these workarounds for conventional pathways can help you out because you have to think outside the box. I can't take anything for granted.

I've learned a lot from my colleagues at Caltech and my running guides, friends to whom I am literally tethered when I run. They tell me where to go, look out for obstacles, and give me feedback on my technique and pacing. It's a team effort, and when we cross the finish line, we do it together."

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

## Five Years of Data



A half decade after its inception, the Tianqiao and Chrissy Chen Institute for Neuroscience at Caltech has expanded to include a new center in data science and artificial intelligence (AI).

Breakthrough techniques in neuroscience generate enormous data sets, such as recordings of the ongoing activities of thousands of neurons and videos of complex animal behavior. But often, neuroscientists have not had formal training in the data science and machine learning methods required to analyze and interpret big data.

Now, the Chen Institute will develop the Chen Center for Data Science and Artificial Intelligence (DataSAI). Lior Pachter (BS '94), Bren Professor of Computational Biology and Computing and Mathematical Sciences, and Pietro Perona, Allen E. Puckett Professor of Electrical Engineering, will serve as co-directors of DataSAI. The Chen Institute is directed by David J. Anderson, Seymour Benzer Professor of Biology and Howard Hughes Medical Institute Investigator. Anderson also holds the inaugural Tianqiao and Chrissy Chen Institute for Neuroscience Leadership Chair.

The center will sponsor programs including a data science and AI boot camp, as well as workshops for students to learn how to interpret large data sets. Caltech students will also have access to the technical equipment to generate and analyze data, and the center will provide them with opportunities for summer internships at off-campus research centers specializing in data science and AI.

Says Pachter: "We are all very excited about the opportunity to develop a program that could lead to the establishment of the Chen Institute at Caltech as an international center for training neuroscience students in data science and artificial intelligence."

## Faces of Psyche

Later this year, a NASA satellite named Psyche will survey a metallic asteroid of the same name to learn more about how it was made, whether it formed in conditions like those of Earth's core, and what its surface looks like. Here on Earth, Psyche's far-out features will be displayed online thanks to the work of Caltech senior Jennah Colborn.

Colborn is not only a physics major who studies astrobiology to search for extraterrestrial life but also an artist who showcases the cosmos in a variety of media to inspire researchers and make science relatable. This double fascination with the stars led her to start an internship last fall with Psyche Inspired, a program that brings together undergraduate students from a variety of disciplines to create artistic works related to the Psyche mission.

For her first of four projects, titled *Faces of Psyche*, Colborn used makeup and digital photography to bring some of the asteroid's physical features to life through a series of portraits featuring other Caltech students.

The first portrait illustrates the asteroid's asymmetry and unique shape. The second shows one aspect of the asteroid's composition: silicate rock and crystal. The third portrait depicts perhaps the most iconic feature of the asteroid: its metal-rich composition. The fourth displays a common feature among asteroids like Psyche: space weathering.

1.

2.

3.

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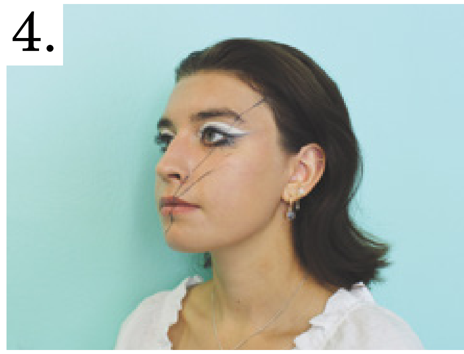


To view all of the Psyche Inspired projects, visit: **psyche.asu.edu/get-involved/psyche-inspired**

# PROCESSION in Person

On October 16, 2021, Caltech celebrated its 2020 and 2021 graduates with an in-person fall commencement event on Beckman Mall in which 299 recent alumni (206 bachelor's, 15 master's, and 78 PhD degree recipients) were afforded their long-awaited opportunity to hear their names read and to process across a stage in front of nearly 600 alumni, friends, and family members. Those who had received their PhDs during two previous virtual commencement ceremonies were hooded.

The event, held in conjunction with the Caltech Alumni Association's Reunion Weekend, brought a number of other graduates back to Pasadena. In attendance at the celebration were three of the 2021 Distinguished Alumni Award recipients: Col. Robert Behnken (MS '93, PhD '97), who offered the keynote address; Barbara Burger (PhD '87); and Laurie Leshin (MS '89, PhD '95), who has since been appointed director of JPL.

# In the Community

## Science Journeys

Caltech Public Programming has launched its second season of a community outreach program that aims to foster a greater understanding of current areas of research and to inspire the next generation of scientists. The Science Journeys series challenges Caltech grad students to prepare 20-minute talks in which they weave together their personal stories with an explanation of their research and why it matters to the world. The talks are geared toward middle and high school students in order to make them accessible to a wide audience.

These Science Journeys, part of the Caltech Signature Lectures Series, are an outgrowth of a program that began in 2005, which included Reel Science and Science Saturdays events. That effort brought more than 50,000 young people to campus to watch an educational film and speak with graduate students about their research and love of science.

**Above:** Katelyn Radford, a PhD student in biochemistry and molecular biophysics, records a Science Journeys presentation for the 2022 season.

While the new format reflects a need for virtual events during the ongoing COVID-19 pandemic, the organizers also wanted to craft a program that offers a deeper dive into the personal stories of Caltech's diverse group of student presenters to show that scientists come from all walks of life.

For example, included among the new slate of 2022 Science Journeys set to premiere soon is Benjamin Idini (MS '19), a PhD student in planetary science, who will present his May talk in both English and Spanish, and include a discussion of how he found his way to Caltech to study Jupiter after growing up on a remote island off the coast of Patagonia in southern Chile. Other research topics covered this year will include structural biology, energy storage, and 3-D–printed nanomaterials.

Although the presentations are prerecorded, viewers can watch the videos live as they premiere on YouTube and submit questions for the speaker, who answers them via live chat. Afterward, the videos remain available for viewing by audiences around the world.

The Public Programming department promotes the events at public and private schools; among homeschooled students, libraries, Boys and Girls Clubs, and other organizations that work with adolescents; and at senior and assisted-living facilities. Staff from the Caltech Center for Teaching, Learning, and Outreach (CTLO) and faculty members recommend the graduate student speakers, who can then avail themselves of the Academic Media Technologies team for audio/visual assistance, while Theater Arts at Caltech director Brian Brophy and Robyn Javier, STEM communication specialist and lecturer in the Division of Engineering and Applied Science (EAS), provide advice on public speaking and presentation skills.

"It's a two-way connection," says Mary Herrera, program coordinator with Caltech Public Programming. "Our team brings the community and young students in to be inspired, and we give the grad students an opportunity to speak to an audience and to learn how to craft a public presentation and communicate their work. It's an education for everyone."

**Watch past lectures and learn more about the Science Journeys series at events.caltech.edu/series/science-journeys**



# Origins

## The Caltech Heritage Project

While working with the American Institute of Physics from 2019 to 2021, historian of science David Zierler spoke with nearly 500 leading physicists. From those interviews, a theme began to emerge.

"Almost everybody I interviewed was either at Caltech, went to Caltech, or did a formative collaboration with somebody at Caltech," Zierler says.

One of those Caltech-related interview subjects was Caltech president Thomas F. Rosenbaum, holder of the Sonja and William Davidow Presidential Chair and professor of physics. As an outgrowth of their discussions, Rosenbaum saw an opportunity to capture the Institute's history firsthand; in 2021, Zierler was named the director of the newly launched Caltech Heritage Project.

Zierler, who earned his PhD in history from Temple University in 2008, will conduct oral histories with faculty, postdocs, staff members, students, scientists, and engineers on campus, at the Institute's offsite facilities, and at JPL. He will also speak with prominent alumni and trustees. The goal, says Zierler, is not simply to study the past but to take ownership of it while also highlighting areas of research focus at the Institute, such as sustainability, medical science, and quantum computing.

"There is current value in understanding an institution's collective memory and putting it to specific strategic use," says Zierler, who previously worked as a historian for the U.S. Department of State, where he assembled classified historical documents from the presidential administrations of Jimmy Carter, Ronald Reagan, and George H. W. Bush. "If we can understand the way things used to be at Caltech, it will help determine how things might best move forward."

In doing so, he hopes to support Caltech's effort to create a campus environment in which people from all backgrounds can share their experiences and perspectives freely to create a more enriching academic experience for everyone.

"There's no better medium than oral history for underrepresented voices to share their perspectives," he says. "That's where you understand that inclusivity is not simply a buzzword but a deeply complex and important topic. In understanding people's culture and personal histories, we can understand how they have shaped and advanced the place that Caltech is."

# A Climate Conundrum

**During the COVID-19 pandemic, carbon dioxide increased at the same rate in the atmosphere despite lower emissions, say researchers from campus and JPL; plus, what is good for ozone reduction is bad for methane removal.**

By Carol Rasmussen

A comprehensive new survey of the COVID-19 pandemic's effects on the atmosphere that uses satellite data from NASA and other international space agencies offers insights into addressing the dual threats of climate warming and air pollution.

"We're past the point where we can think of these as two separate problems," says Joshua Laughner, lead author of the study and a former postdoctoral fellow in the Division of Geological and Planetary Sciences who now works at JPL, which Caltech manages for NASA. "To understand what is driving changes to the atmosphere, we must consider how air quality and climate influence each other."

Published in November 2021 in the *Proceedings of the National Academy of Sciences*, the paper developed out of a workshop sponsored by the W. M. Keck Institute for Space Studies and led by scientists on campus and at JPL.

The COVID-19 pandemic and resulting limitations put on travel and other economic sectors by countries around the globe drastically decreased air pollution and greenhouse gas emissions within just a few weeks. However, while carbon dioxide ($CO_2$) emissions fell by 5.4 percent in 2020 compared to the previous year, the amount of carbon dioxide in the atmosphere continued to grow at about the same rate as in preceding years. While the drop in emissions was significant, the growth in atmospheric concentrations of $CO_2$ was within the normal range of year-to-year variation caused by natural processes. Also, the ocean did not absorb as much carbon dioxide from the atmosphere as it has in recent years, probably due to the reduced pressure of carbon dioxide in the air at the ocean's surface.

"During previous socioeconomic disruptions, like the 1973 oil shortage, you could immediately see a change in the growth rate of $CO_2$," says David Schimel, head of JPL's carbon group and a co-author of the study. "We all expected to see it this time, too."

The study also examined atmospheric nitrogen oxide (NOx) levels. In the presence of sunlight, nitrogen oxides can react with other atmospheric compounds to create ozone, a gas that is a danger to human, animal, and plant health. Although the study found that COVID-related drops in nitrogen oxides led to a reduction in ozone in most places around the world, its satellite measurements uncovered a less positive effect of limiting NOx. Nitrogen oxides react to form a short-lived molecule called the hydroxyl radical, which plays an important role in breaking down long-lived gases in the atmosphere. By reducing NOx emissions—as beneficial as that was in cleaning up air pollution—the pandemic also limited the atmosphere's ability to cleanse itself of another important greenhouse gas: methane.

"NOx chemistry is this incredibly complicated ball of yarn, where you tug on one part and five other parts change," Laughner says.

Molecule for molecule, methane is far more effective than carbon dioxide at trapping heat in the atmosphere. Estimates of how much methane emissions dropped during the pandemic are uncertain, but one study calculated the reduction at 10 percent. However, as with carbon dioxide, the drop in emissions did not decrease the concentration of methane in the atmosphere. Instead, methane grew 0.3 percent faster in the past year than in the previous four—a faster rate than at any other time in the last decade. With less NOx there was less hydroxyl radical to scrub methane away.

Notably, emissions returned to near pre-pandemic levels by the latter part of 2020, despite reduced activity in many sectors of the economy.

"This suggests that reducing activity in these industrial and residential sectors is not practical in the short term" as a means of cutting emissions, the study noted. "Reducing these sectors' emissions permanently will require their transition to low-carbon-emitting technology."


# The Resnick Sustainability Center's design will reflect the Institute's innovative approach to education and research in environmental issues.

**By Kimm Fesenmaier**

In the fall of 2024, students and researchers across Caltech will have a new hub from which to investigate challenges in global sustainability. Gracing the western edge of campus, the building, which will be known as the Resnick Sustainability Center (RSC), will aim to inspire onlookers with a three-story-high undulating glass facade supported by a mass-timber frame and a slew of sustainable building features. But beyond these attributes, it will also serve as a defining component of a major sustainability effort on campus.

That endeavor, which touches everything from research and education to diversity and inclusivity, has been fueled by the $750 million pledge from Lynda and Stewart Resnick, owners of The Wonderful Company, in 2019. Its goal: to focus and harness the Institute's many talents to tackle issues related to energy and the utilization of resources in a world experiencing rapid climate change.

"In certain ways, Caltech is conducting an experiment that really hasn't been done in sustainability," says Jonas Peters, director of the Resnick Sustainability Institute (RSI), which was originally established in 2009 with a gift from the Resnicks and a matching gift from the Gordon and Betty Moore Foundation. "We are building an institute that really tries to pull, essentially, all of the campus toward problems in sustainability. We need all hands on deck."

The Resnick building, designed by the Yazdani Studio of CannonDesign, will replace the now-demolished Clifford S. and Ruth A. Mead Memorial Undergraduate Chemistry Laboratory, home to Caltech's undergraduate chemistry labs for 40 years (see Endnotes, page 40). Unlike the stand-alone Mead, the new building will incorporate a breezeway through the structure that allows pedestrians to access the walkways beyond. In this way, it will serve as a gateway of sorts connecting the northern and southern parts of campus along Wilson Avenue.

True to the center's name and purpose, it will incorporate a variety of sustainable materials and features. The 79,500-square-foot project, which includes an underground level, is not only on track to earn LEED platinum certification, the highest level of the LEED (Leadership in Energy and Environmental Design) rating system, but, more importantly, is designed to open new figurative portals to sustainability in the realms of research, education, and societal impact.

## Sustainability education

In addition to supporting research and discovery, the RSC will serve as an educational gateway. The undergraduate chemistry labs formerly housed in Mead Lab will all be relocated to the second floor of the Resnick building. Since all Caltech first-year students must take an introductory chemistry lab course, every Techer will have at least one course in the new building. They will be introduced to the concept of sustainability through a reimagined curriculum that grounds their education in an understanding of society's environmental challenges and instills an imperative to search for solutions across disciplines.

"We went beyond just thinking about the really important task of moving the undergraduate chemistry labs and thought about how to bring the ethos of sustainability into play in this new space and make this whole floor a real resource for campus," says geochemist Jess Adkins.

Since November 2019, he and chemist Theo Agapie (PhD '07) have led an education committee charged with exploring paths to better implement sustainability education across campus. The committee recommended that the RSC building include flexible lab and storage areas that could meet the needs of sustainability-related courses from other divisions, and also provide state-of-the-art laboratory space for chemistry training.

One of the three teaching lab spaces on the second floor is being designed as a flexible research and learning space that could be used for courses in different divisions. It will include storage space not only for chemical equipment but also for instrumentation and materials for labs in biology, geology, and applied engineering. This will enable courses to cross the traditional boundaries of the disciplines as well. For instance, a chemistry class using this space might go out into the field, perhaps to one of the ponds around campus or up into the San Gabriel Mountains, to collect soil samples and bring them back to the lab to analyze in a variety of ways throughout the term, including using the microscopes common in biology and geology classes.

"That's very different than anything that's currently in the undergraduate chemistry curriculum," Adkins says. "The building will now be equipped for this interdisciplinary flavor of lab space."

The education committee also conducted a review of courses offered on campus and the locations in which they are taught. The review revealed a strong need for more spaces that can accommodate between 40 and 100 students and can be used as active-learning, or "flipped," classrooms. In such spaces, unlike traditional lecture halls, students sit around tables, allowing instructors to easily switch between lectures and more interactive, collaborative activities. STEM education research has established that such classrooms provide students with better learning experiences.

As a result, the Resnick building will also include two 48-person, active-learning classrooms. Designed in consultation with experts from Caltech's Center for Teaching, Learning, and Outreach, these contiguous rooms will be connected by a retractable wall that can be pushed open to make one larger space.

"It was quite apparent that as we move forward with sustainability education, there will be a strong need for classrooms like these that promote active learning," Agapie says.

Changes are also coming to the curricula that will be taught within those innovative classrooms. The education committee recommended that, rather than develop a single new core course that focused on sustainability, existing courses should be infused with sustainability concepts. This could be done by working in more sustainability-related examples, problem-set questions, field trips, and exercises.

For example, when core instructors introduce Beer's law, which states that the absorbance of a solution, including a gaseous solution, is directly proportional to its concentration, they might explain the basics of the greenhouse effect. A discussion of predator–prey relationships could be employed to illustrate systems thinking, which seeks to understand individual behavior by looking for broader, complex structures and relationships, such as ecosystems. In tandem, faculty members are creating new sustainability-related courses, such as a course called Climate Change Impacts, Mitigation, and Adaptation, which was offered in the second term of the 2021–22 academic year by a team of faculty members from across Caltech: Paul Wennberg, the R. Stanton Avery Professor of Atmospheric Chemistry and Environmental Science and Engineering; Neil Fromer, executive director of programs for the RSI; and Jean-Laurent Rosenthal (PhD '88), the Rea A. and Lela G. Axline Professor of Business Economics.

**Above:** Architectural rendering of the Resnick Sustainability Center showing the breezeway.

As of this academic year, Caltech has begun to offer an undergraduate option in environmental science and engineering with tracks in chemistry and physics.

Such changes are likely to have an impact on Caltech's inclusion and diversity efforts as well: studies show that students from historically marginalized racial and ethnic minorities, along with first-generation college students, are seeking out programs that have direct community impact. Programs in sustainability, like those being envisioned and implemented at Caltech, can fit that bill, the faculty members noted.

Agapie says this was evident at a recent Future Ignited workshop hosted by Caltech, where undergraduate students of color from across the country were given the opportunity to speak with Caltech faculty members about graduate school options and prospects.

"RSI and sustainability really spoke to people who might not see themselves following a typical path to the traditional disciplines," he says.

## Sustainability research

Unlike the vast majority of Caltech research facilities, the new building will not house individual faculty members and their labs. Instead, it will provide equipment, space, and resources divided among several research centers designed to support the core initiatives launched by the RSI: Sunlight to Everything; Climate Science; Water Resources; and Ecology and Biosphere Engineering.

"We decided that there was a critical need for new types of facilities with new capabilities to execute the research mission that we are pursuing," Peters says.

When it opens, the Resnick building will house four centers that will each offer specialized equipment and resources. Each will benefit from the expertise of a staff scientist who can support researchers using the specialized equipment and resources the center offers.

"It's facilities like these, with brilliant staff who keep them running and who collaborate closely with faculty and students and postdocs, that really makes breakthrough research at Caltech much more possible than it would otherwise be," Peters says.

The **Solar Science and Catalysis Center (SSCC)** will build on Caltech's established expertise in the solar energy realm. A particular focus will be on the synthesis of new materials that can harness solar energy to make renewable fuels as well as those needed to speed up the chemical reactions that convert ubiquitous natural resources like air and water into usable energy-rich molecules. The new building will also include a "solar roof," where photovoltaic devices can be tested under real-world conditions.

The **Remote Sensing Center (RSC)** will be Caltech's first dedicated campus space in which faculty and students can develop and guide satellites of different sizes designed to measure or monitor soil moisture, sea levels, and methane emissions, among other activities.

The **Ecology and Biosphere Engineering Facility (EBEF)** is designed to support innovative interdisciplinary research to understand how diverse life-forms, from microbes to insects to plants, interact with their environments. EBEF researchers will cultivate, analyze, and manipulate diverse organisms in environmental contexts. The facility will allow for the control and visualization of gene expression at single-cell resolution, and will empower researchers to engineer ecosystems at their most fundamental level. Researchers will also be able to conduct soil studies under variable conditions, facilitating studies of organisms and how they respond to changes in climate as well as in resources such as water.

The goal of the **Translational Science and Engineering Facility (TSEF)** is to provide space for the Caltech community to pursue demonstration projects that cannot be accommodated in existing labs: to scale up and test early-stage technologies for potential translational impact. The space is designed to maximize flexibility to serve a wide range of projects. It will also include a high-bay space that will allow for research on larger structures, such as satellites and industrial-scale chemical-processing equipment.

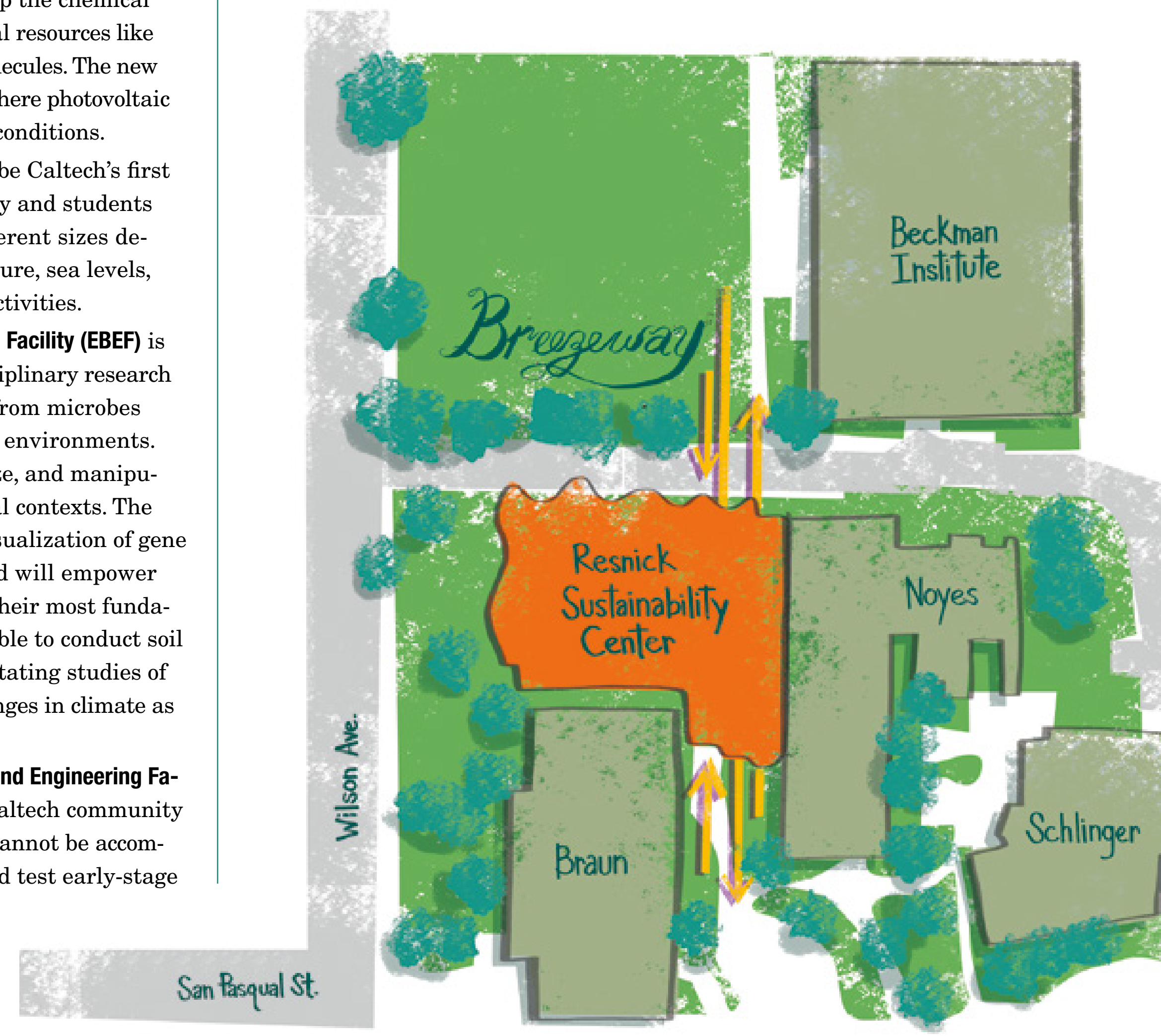
While Peters notes that the vision for the building, and the reimagined approach to sustainability-related curricula and research it has sparked, might seem ambitious, he has already seen the power of problems in sustainability to engage a broad swath of the Caltech community and how creative their cross-disciplinary approaches to solutions can be.

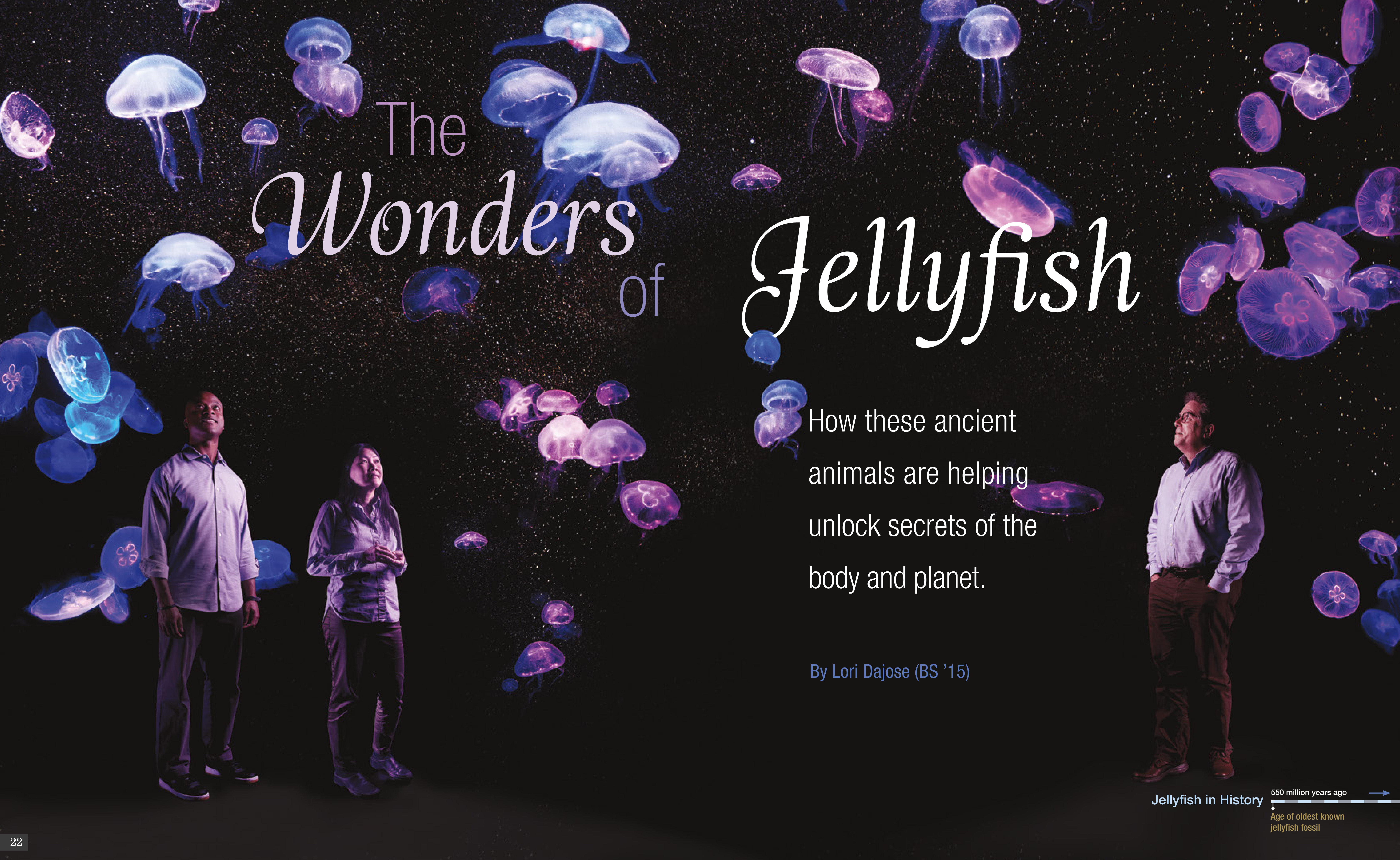
"Once you shine attention as well as resources on these problems, you tend to draw remarkably capable people in," Peters says. "After all, these are issues that affect us all."

**Jess Adkins** is the Smits Family Professor of Geochemistry and Global Environmental Science.

**Theo Agapie** is a professor of chemistry and the executive officer for chemistry.

**Jonas Peters** is the Bren Professor of Chemistry and director of the Resnick Sustainability Institute.





# The *Wonders* of *Jellyfish*

How these ancient animals are helping unlock secrets of the body and planet.

By Lori Dajose (BS '15)

Jellyfish in History

550 million years ago

Age of oldest known jellyfish fossil

Caltech's Chen Neuroscience Research Building is a maze of pristine white hallways and white tile floors, long lab benches, and whirring machinery around every corner. Deep within these corridors, if you can find it, is a wooden door marked not with a sign but rather a stuffed jellyfish made of felt and ribbons. Sliding back this door reveals a darkened room lined with identical vats of gently bubbling water, each illuminated by a row of dim lights. Look closely, or you might miss them: ghostly translucent circles, smaller than a pinkie nail, disappearing and reappearing as they drift through the liquid.

Older than the dinosaurs, older even than the rings encircling Saturn, jellyfish have been swimming Earth's oceans for 550 million years, surviving drastic environmental changes relatively unscathed. Over the past decade, Caltech researchers David Anderson, John Dabiri (MS '03, PhD '05), and Lea Goentoro have begun to tap into the powerful abilities of these primitive animals to answer questions about our changing planet and the common properties underlying life itself. In the process, the translucent creatures have opened new windows into our understanding of neuroscience, the deep ocean, and biological regeneration.

"There aren't a lot of labs in the country that have jellyfish," notes Dabiri, an aeronautical and mechanical engineer. "Which is why it's exciting that we now have three labs at Caltech working on them."

## Reading minds

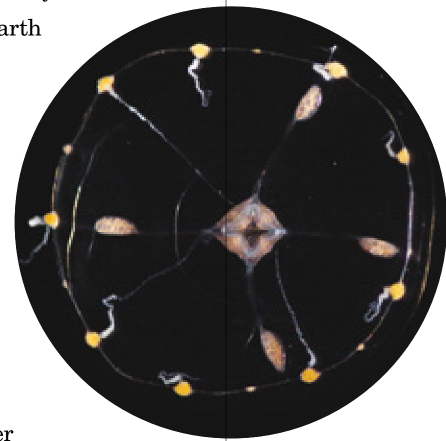
The felt jellyfish marks the entrance to the laboratory of Anderson, a neuroscientist and the director of Caltech's Tianqiao and Chrissy Chen Institute for Neuroscience. Over the past four years, he and postdoctoral scholar Brady Weissbourd have worked to develop a toolbox of genetic methods they use to tinker with the brain cells of the microscopic jellyfish *Clytia hemisphaerica* in order to study the neuroscience of behavior.

Jellyfish are perhaps a counterintuitive animal with which to study neuroscience, because the animals do not actually have a brain as we know it. Rather than being centralized in one part of its body, the jellyfish brain, which is composed of approximately 10,000 neurons, is diffused across the animal's entire body like a net. The Anderson lab, which focuses on the neurobiology of emotion, decided to develop a jellyfish model for studying how behavior is coordinated in the absence of a centralized brain.

**Brady Weissbourd,** postdoctoral scholar in the Anderson laboratory, examines batches of genetically engineered *Clytia hemisphaerica*.

"These types of extreme biology are useful to understanding life as we know it," Weissbourd says.

Over 580 million years ago, while Earth was thawing from extensive glaciation, primitive nervous systems began to appear in animals. It was then that a sort of schism of evolution happened: on one side, the decentralized nervous systems of cnidarians like sea anemones, coral, and jellyfish, and on the other, essentially everything else, with a few exceptions.



*Clytia* seen from above. One centimeter across when mature, the jellyfish has a central mouth and symmetric tentacles along its circular body.

The lack of a complex centralized brain, however, has not seemed to hinder jellyfish evolutionarily. Their unusual brains have myriad different abilities than ours; for example, their decentralized control of behavior enables a surgically removed jellyfish mouth to carry on "eating" autonomously without the rest of its body.

"By studying these weird creatures that branched off evolutionarily a long time ago, we might be able to learn about what the first neurons might have looked like or the first neural networks," Weissbourd says.

To gain these insights, Anderson's team genetically modified *C. hemisphaerica* so their neurons would light up with a fluorescent protein when firing. The idea behind this was to enable the researchers to observe jellyfish neural activity under a microscope in real time as the animals swim around and behave normally. Though this kind of modification has been done in other laboratory animals such as mice and fruit flies, developing a new so-called transgenic animal was not easy. The main challenge for the team was determining how to insert new genetic material that encodes for the fluorescent protein into the jellyfish genome and link it with the processes that make neurons fire.

"There was a lot of uncertainty at the beginning," Weissbourd says. "We were trying a lot of different methods. David [Anderson] and I would talk about, 'How long are we going to try to get a transgenic jellyfish before we stop trying?'"

After nearly four years, it worked. Using this new tool, the laboratory first sought to crack the neural code underlying how *Clytia* eat. When a jelly snags a brine shrimp in one of its tentacles, it folds its body to bring the tentacle to the mouth at its center. By examining the chain reactions of neural activity as the animals ate, the team identified certain neurons responsible for that inward folding of the body.

Additionally, the researchers found a remarkable degree of organization in the network of jellyfish neurons, which originally seemed diffuse and unstructured, and only became visible with their fluorescent system; as it turns out, *Clytia*'s neurons are arranged, surprisingly, in radial wedges, like slices of a pizza.

"Studying how neural circuits control jellyfish behavior should give us insights into which aspects of human brain function can be traced back to the earliest stages of neural evolution and which aspects are more recent inventions," Anderson says. "In addition, understanding how their behavior and reproduction are controlled will help us learn to live with, control, and conserve jellyfish."

## Undersea explorers

While Anderson continues to uncover the secrets of the jellyfish mind, Dabiri and his colleagues are hoping to harness the animals' abilities in their natural habitat to help researchers explore the deep ocean and improve our understanding of climate change.

The ocean comprises 99 percent of Earth's habitable volume and is home to at least 2 million marine species. Because the deep ocean is opaque to most of the electromagnetic spectrum, it is, in a way, invisible. But the processes in the deep ocean are critical to human survival on this planet; for example, the ocean acts as a reservoir to sequester carbon and prevent it from being released into the atmosphere and warming the planet. Yet, human understanding of these processes has been limited by our ability to access the ocean's depths. Most of the data available are thus biased to a thin strip of its surface.

"We know more about the surface of Mars and Venus than we do about the deep ocean," says Dabiri. "If I was given the choice between suiting up and going to Mars versus going to the bottom of the ocean, of course I would pick the ocean."

However, Dabiri is hoping that humans will not have to develop complex deep-ocean suits to perform this feat. Instead, he plans to use jellyfish, which are natural explorers in these environments.

The jellyfish species *Aurelia aurita* has been discovered as deep as the Marianas Trench, nearly 7 miles under the surface. The Dabiri lab is currently developing tiny, lightweight devices that can be attached to these jellyfish, like a harness onto a horse, and that can steer the animals around the ocean while simultaneously making measurements of oceanic parameters such as oxygen

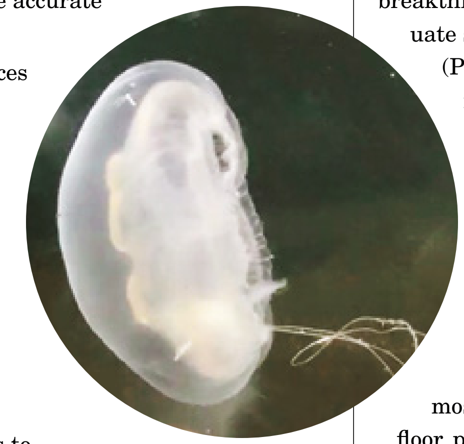
(Years are approximate)

400 million years ago

First land plants evolve on Earth

levels and temperature. Being able to measure these parameters would be important to creating more accurate models and predictions of climate change.

The team has already shown that the devices can be attached to the animals and induce them to swim faster and more efficiently with no damage or stress to the jellies. The next step is to program the devices with artificial intelligence algorithms that will enable the small-scale apparatuses to autonomously steer the jellyfish through strong ocean currents to desired locations. Ultimately, Dabiri envisions being able to send millions of these tech-enhanced jellies out into the ocean.



An electrical current is used to regulate the *Aurelia's* pulse in order to increase its speed and efficiency in the water.

"I think it's poetic that jellyfish can help us to understand climate change, since our success in the effort will ultimately help to protect their natural habitats," Dabiri says.

The depths *Aurelia* will explore are echoed by the setting of Dabiri's subterranean lab, which sits two floors below the surface of Caltech's campus. There, gently drifting *Aurelia* live in an aquarium with a rounded bottom, which prevents them from getting stuck in a corner. The lab also houses a huge, 4,300-gallon tank with which researchers can measure the performance of the bionic jellyfish; behind the tank, a mural of the futuristic jellies is lensed through the distortion of the water. For even larger-scale research, a two-story tank, closer to 5,000 gallons, is just a few doors away down the underground corridors.

## *Sleep* with the jellyfishes

Goentoro, a biologist, first met Dabiri when she joined the Caltech faculty in 2011. Originally, her research focused on how cells send messages to one another through proteins and other molecules. But those projects were taking months to set up and, in the meantime, over chance conversations at Caltech's Red Door Café, Goentoro had become intrigued by Dabiri's jellyfish studies. So she devised a side project for one of her graduate students to study the so-called moon jellyfish, *Aurelia aurita*.

"Lea has so many creative ideas, and she is an innately creative person," Dabiri says. "For a long time, I had preached the gospel that there's so much about jellyfish we don't know, largely from an engineering perspective. And now, she's come across these really interesting biological discoveries."

Goentoro had no idea that, within five years, this side project would reshape the entire focus of her research, which seeks to understand how biological systems are built and how they function. A major jellyfish-related breakthrough came in 2017: in a study led by then graduate students Ravi Nath (PhD '18), Claire Bedbrook (PhD '18), and Michael Abrams (PhD '18), the team made headlines for discovering the seemingly simple fact that the jellyfish *Cassiopea* sleeps, just like humans. Goentoro's lab partnered on the research with fellow Caltech researchers Paul Sternberg, the Bren Professor of Biology, and Viviana Gradinaru (BS '05), professor of neuroscience and biological engineering, in whose labs Nath and Bedbrook worked.

*Cassiopea* is a genus of jellyfish that spends most of its life sitting upside down on the ocean floor, pulsating every few seconds. The team showed *Cassiopea* exhibits reduced pulsating at night, and it takes longer to arouse in this period of decreased activity. The team also prevented the animals from entering this quiescent state by pulsating water at the jellies throughout the night and saw that they were more likely to fall into the quiescent state during the day. These discoveries provided the evidence needed to prove the animals do indeed sleep.

"It may not be surprising that jellyfish sleep; after all, simple organisms like worms and fruit flies have also been shown to sleep," Goentoro says. "But our discovery that *Cassiopea* also enters into a regular sleeping state, just like us, now makes jellyfish the most evolutionarily ancient animal known to sleep. Finding out things that are common to all life makes you see the world, and yourself, in a profoundly different way. I look around me: the birds, the beetles, the trees, we are all deeply connected. The collaboration between the three laboratories really made this possible."

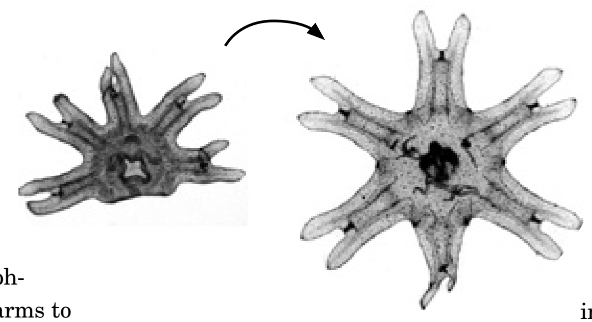
Graduate student **Nina Mohebbi** swaps out an old seawater battery for a new one on a test platform in the Dabiri lab. These batteries operate in the ocean by using ambient seawater as the battery's electrolyte.

## *Coaxing* regeneration

The sleep study was a major turning point for Goentoro's research, but the definitive pivot occurred with a study of *Aurelia* ephyra, the infant stage of the jellies studied by Dabiri's lab.

Although the mature *Aurelia* can grow to the size of a dinner plate, its ephyra are just 5 millimeters across. Their eight tiny symmetrical arms pulsate in rapid synchronization like a blinking eye or beating heart as they swim through water. When they are not actively swimming, you could easily mistake them for pieces of debris or algae.

In 2015, Abrams, the graduate student who worked on the sleep paper, was studying how ephyra repair themselves after losing one or more of their eight arms, in the same way human skin repairs itself after a cut. The team discovered that within the first two days after injury, an *Aurelia* ephyra would reorganize its existing arms to be symmetrical and evenly spaced around the animal's disc-like body. This so-called symmetrization occurred regardless of whether the animal had as few as two limbs remaining or as many as seven; ultimately, the process was observed in three additional species of jellyfish ephyra.



Under certain conditions, *Aurelia* ephyra will regrow a missing arm.

Abrams and co-author Ty Basinger also observed another phenomenon while studying symmetrization: in some rare cases, the jellyfish would begin to regrow a missing arm. While some animals, including certain species of jellyfish, are known to have the ability to regenerate damaged body parts, this had never been shown in *Aurelia*. This discovery gave the team an opportunity to look for ways to enhance these unexplored regeneration abilities. Over the next five years, the team examined various molecules and conditions that might induce arm regeneration in *Aurelia*. They found that all it took was the hormone insulin and the amino acid leucine.

"These are simple molecules that are promoting regeneration," Goentoro says. "This was surprising because, if regeneration could be induced at all, we expected to find signaling molecules and transcription factors that pattern tissues. Insulin and amino acids are typically associated with metabolism, how our body processes food into energy. Our work suggests that modulating metabolism may be what it takes to unlock regeneration."

The researchers decided to see if these same simple conditions could induce regeneration in two other laboratory animals not known to regenerate: specifically, the fruit fly *Drosophila melanogaster* and the laboratory mouse. Though *Drosophila* have never been shown to regrow limbs, the team found that increased levels of insulin and leucine in the flies' food led to some degree of regrowth in 49 percent of flies. In mice, 10 percent were able to regrow at least part of an amputated toe when their diets were supplemented with leucine and sugar.

The work suggests that there is a latent, untapped ability to regenerate after injury that is shared by animals as primitive as jellyfish and as complex as mice.

"Some people have thought for some time that all animals have a latent ability to regenerate," Goentoro explains. "The biggest surprises are how simple the key is that can unlock this capacity, and that the same key works across animals. Just a common amino acid and sugar can coax these complex structures to regrow. The simplicity brings closer the hope that someday we can coax body parts to regrow in humans."

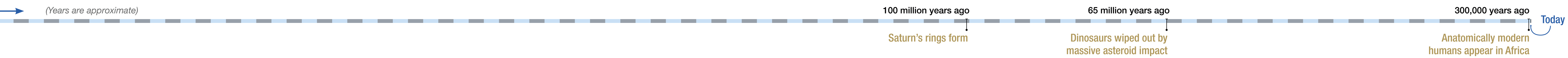
Regeneration, Goentoro says, will be the focus of her lab going forward, as she and her team seek to learn more about the molecular pathways that are triggered during regeneration and the simple dietary conditions that might trigger them.

"I had no idea things would go this route," she notes. "That's what I love about Caltech. I get to be inspired by the outside-of-the-box research my colleagues are doing."

**David Anderson** is the Seymour Benzer Professor of Biology; the Tianqiao and Chrissy Chen Institute for Neuroscience Leadership Chair; director of the Tianqiao and Chrissy Chen Institute for Neuroscience; and a Howard Hughes Medical Institute investigator. His work is funded by the Howard Hughes Medical Institute, Caltech, National Institutes of Health, and the Caltech Center for Evolutionary Science.

**John Dabiri (MS '03, PhD '05)** is the Centennial Professor of Aeronautics and Mechanical Engineering. His work is funded by a MacArthur Foundation fellowship, the National Science Foundation, and the Office of Naval Research.

**Lea Goentoro** is a professor of biology. Her work is funded by the Natonal Science Foundation, National Institutes of Health, and Caltech's Center for Environmental Microbial Interactions.



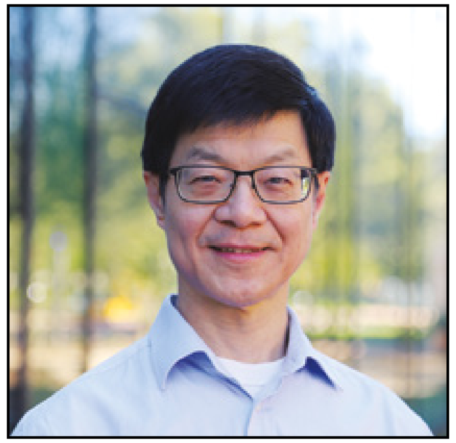
# The Grid Gets Smart

Adaptive electric vehicle chargers and advanced battery designs are some of the ways Caltech researchers are building a more sustainable electric grid.

By Andrew Moseman

Picture an office parking lot lined with electric-vehicle (EV) chargers. As a new workday dawns, dozens of drivers plug in and the chargers pump power to all those thirsty vehicle batteries. Although it is convenient for drivers to recharge their cars while they work, this sudden demand for voltage stretches the parking lot's electrical system to its limits.

Electrical engineer Steven Low knew this problem would grow more acute as electric vehicles became more popular and placed more of a strain on the energy grid. But he also realized that all the vehicles in this scenario would not need to draw maximum charge simultaneously. So his group invented the Adaptive Charging Network (ACN), a flexible platform capable of real-time communication, measurement, and actuation. When drivers plug into one of his chargers, they tell a smartphone app how much charge they need and how long they plan to stay. Low's algorithm uses this information to direct energy to vehicles with the most urgent need. For example, one person may leave their EV parked for a full workday but need relatively little energy to top off the battery. That person could wait until late in the day to charge. Another employee, who needs to charge before driving to a lunchtime meeting, could begin to receive electricity immediately. Low's ACN technology, licensed through a startup called PowerFlex, is now in Caltech's parking structures and is being deployed elsewhere in California.

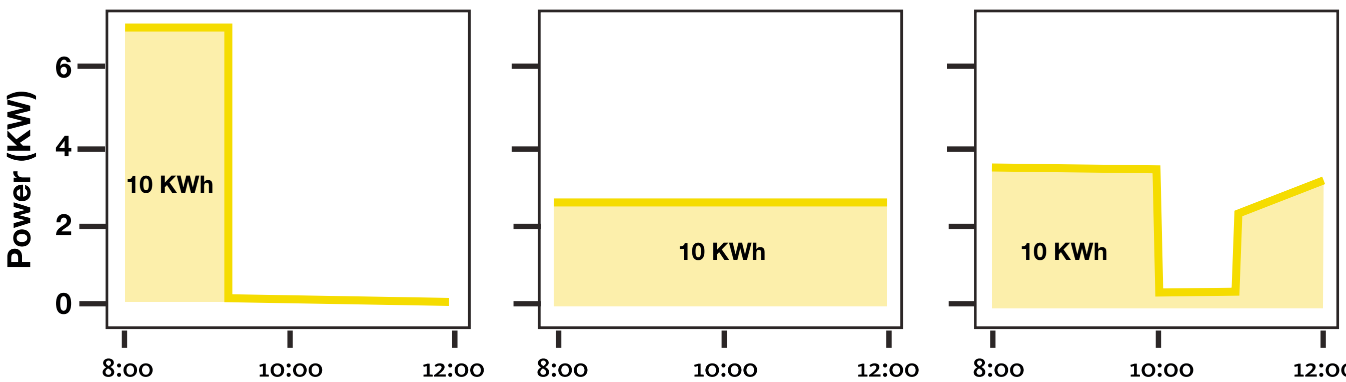


Flexible EV chargers are emblematic of the kinds of solutions required to build the next generation of energy grids: so-called smart grids that integrate information technology to flexibly and responsively manage society's energy needs in the decades to come. Not that the grid of today has not served society well: it represents one of the greatest engineering achievements of the 20th century, Low says. The modern grid is a complicated web of power lines, transmission towers, transformers, and other physical infrastructure. Combined with the economic forces that manage energy markets, today's grid constitutes a gigantic system that transmits and distributes electricity exactly where and when it is needed across regions, or even continents, to facilitate all aspects of modern life.

But Low and others warn that this grid is unprepared for the challenges of the 21st century, particularly a major move toward renewable energy sources such as solar and wind power as a way to slow climate change.

A recent study in *Nature Communications*, co-authored by Nate Lewis (BS '77, MS '77), the George L. Argyros Professor and professor of chemistry, demonstrated solar and wind power could meet most of the world's energy demands. However, according to the U.S. Energy Information Administration, more than 60 percent of electricity generated in the United States in 2020 still came from fossil fuels, mainly natural gas and coal. What is more, today's electricity grid was designed to distribute a steady flow of electricity created by burning fossil fuels. But the sun and wind do not provide a steady flow: the sun does not always shine and the wind does not always blow; thus, these renewable sources of energy are variable in a way that does not mesh well with the grid. Meanwhile, electricity demand is set to soar, especially as the world embraces EVs in an attempt to decarbonize the transportation sector.

"The current grid will very soon hit a wall where, when we add renewable energy, it sits unused because the demand isn't there at a time when the solar is running," says computer scientist Adam Wierman. That is why he, Low, and other Caltech researchers are working on ways to break down that barrier to help empower an energy transformation.




## Balancing act

A smarter grid calls for equal parts technology and strategy. On one hand, the world must construct increased renewable energy capacity if countries are to meet most or all of their energy needs using green sources. But it is not enough just to build more wind and solar farms.

"We have to be prepared for the sun to not be shining or the wind to not be blowing," Wierman says. "If you're not smart about running the grid, then for every large solar farm you install, you have to still build a traditional generator. As long as you're doing that, you're not getting the benefit from the renewable generation that you should."

Wierman's research focuses on how to make the grid more compatible with the uncertainty of renewable energy, which starts with a simple concept: if our energy supply is a little less predictable, then our energy demand needs to be a little more flexible.

For instance, suppose the weather forecast calls for a cloudy but hot day tomorrow. Most people will want to run their air conditioners, but less solar energy will be available. One solution would be pre-cooling. It takes more energy to cool a building than to keep it that way, Wierman says. People and businesses alike could run their ACs earlier in the day when demands on the grid are lower, so the temperature in their home or building is comfortable when the hottest part of the day rolls around.

This kind of time flexibility will be crucial to a more sustainable grid, Wierman says. Electric cars could charge when the sun is out and the largest amount of solar energy is available. Dishwashers and laundry machines could ask their owners whether they need those clothes and dishes cleaned right away, or if they could wait a few hours until the grid is less stressed. The enormous data centers run by technology giants such as Google and Amazon could schedule energy-intensive activities, like archiving their data, for times that maximize renewables.

But this smart scheduling alone will not fix the problem; it also requires a major overhaul in how the grid is managed, Wierman explains. Today's system relies on a centralized approach, meaning there must be a human in the loop to make sure enough electricity is directed to where it is needed. The smart grid, on the other hand, uses a decentralized approach, in which everything from dishwashers to data centers can interact with and glean information from the grid to optimize energy use without human intervention.

"You want a building to be responsive to what's going on in the grid more broadly," Wierman says. "You want EV charging to be responsive to what's going on in the grid more broadly as well rather than just have this myopic view of what it needs now. It's about making sure the grid can be both more reliable and more sustainable."

Steven Low **(above left)** and a graphic **(left)** that depicts different ways his smart chargers could deliver 10 kilowatts of energy to an electric vehicle during the day. Spreading out the energy demand eases the strain on electric infrastructure. **Above:** Adam Wierman.

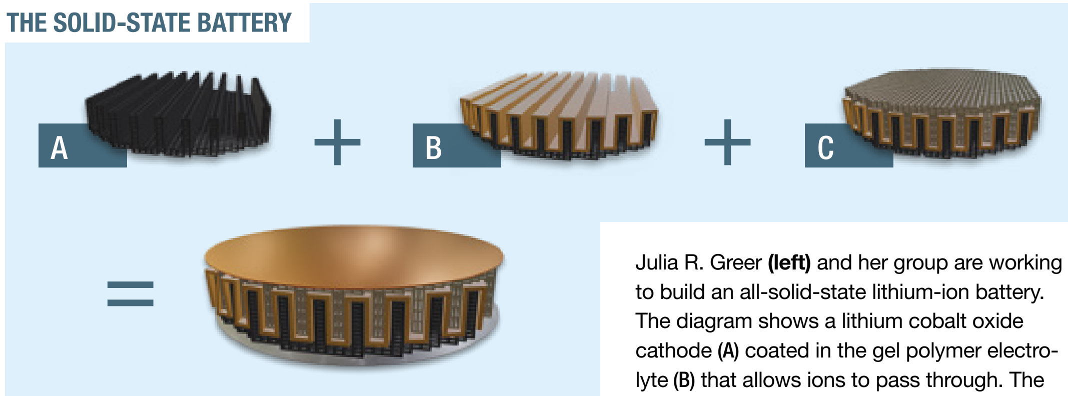
## Bettering the battery

When a sweltering heat wave smothered California in August of 2020, it caused rolling blackouts at a level not seen in two decades. Yet all the energy needed to stabilize the grid and avoid those outages was right there, parked in garages across the Golden State. There are roughly 600,000 all-electric vehicles in California, Low says, and if just a third of those cars had fed 10 percent of the energy in their batteries back into the grid, the blackouts could have been avoided entirely.

It may sound far-fetched that the battery in your electric car could mitigate a power outage, Low says, but the idea illustrates the importance of inventing clever energy-storage solutions, another crucial component of a smarter, more sustainable, electrified future. Innovative battery technologies could allow EVs to drive farther between charging stops, which would improve the lives of drivers and potentially lower the stress on the grid. And the ability to store energy at a large scale, whether in giant batteries or through other means, would help the grid to mitigate the on-and-off nature of renewable energy sources.

Already, Caltech's hometown of Pasadena has experienced stability problems with the grid because of the growing use of solar panels and electric vehicles, both of which are trends the city promotes. In an effort to help the city stabilize energy supply and distribution, Low and Wierman are working with the city's utility provider, Pasadena Water and Power, on a project to install batteries that could store solar and wind energy to use at times when energy supply is low.

"We help them ask, 'Where should we install those batteries? How much battery storage do you need? And how do we schedule the charging and discharging process of those batteries onto the grid in the most efficient way?'" Low says.




Julia R. Greer **(left)** and her group are working to build an all-solid-state lithium-ion battery. The diagram shows a lithium cobalt oxide cathode **(A)** coated in the gel polymer electrolyte **(B)** that allows ions to pass through. The carbon anode is then added **(C)**, followed by the final step of adding the current collectors to make a full battery. **Right:** Kimberly See, whose lab aims to improve battery technologies through alternative chemistries.

Other Caltech researchers, like materials scientist Julia R. Greer, are pushing the limits of the batteries themselves. The Greer lab focuses on engineering at the nano- and microscale, creating materials that can be extremely strong, lightweight, and failure-resistant all at the same time. Her research uses nanostructures as building blocks to construct "architected materials" that bring elusive and exotic abilities to the scale of everyday human experience, and it did not take long for her to realize that batteries could be one of the most immediate applications for this work.

"Our micro-architected materials are lightweight and mechanically resilient; they have unique functionalities, unusual properties, and combinations of properties that haven't really been possible before," Greer says.

Armed with new materials, researchers like Greer are trying to reinvent how batteries are designed and built. Most commercial batteries, whether they power a TV remote control or a car, contain two electrodes: the positively charged cathode and negatively charged anode. Between the two is a liquid or gel called the electrolyte. Charged ions pass through the electrolyte on their way from one electrode to the other. Those are the essential components, Greer says, but building a stable, safe, and reliable battery invariably means adding in a variety of other elements. The problem is, these additions make the battery heavier, more wasteful, and less powerful.

Greer envisions a battery in which all the components add to its power and efficiency. One example: her lab is developing a design in which a battery's anode and cathode are not fixed points at the far end of a battery. Instead, the anode and cathode materials are in the form of 3-D lattices that comprise the volume of the battery. The two different material lattices are interlocked without contacting one another, with a polymer electrolyte between them providing both a cushion and ion transport medium. In such a setup, the ions carrying the electrical charge need only travel a small distance to the corresponding electrode that is directly across from them as opposed to traveling across the length of the whole battery.

This short distance between the cathode and anode would allow Greer to experiment with the use of a solid electrolyte between them rather than a liquid. The so-called solid-state electrolyte is a hot topic in current battery research, Greer says. A big reason for the interest in solid-state electrolytes is that tiny spikes called dendrites grow on the metal electrodes, especially in high-performance metals like lithium. These spikes degrade the battery's lifespan and, in some cases, can cause a short or fire. The idea is that solid-state electrolytes could physically push against the electrode and slow the dendrites' growth.

But solid-state electrolyte batteries have their own challenges, including that ions typically cannot move as freely through a solid as through a liquid or gel, making the short traveling distance in Greer's design essential.

In addition to rethinking battery design, Caltech researchers are scouring the periodic table for better materials. As chemist Kimberly See notes, many of the materials used in today's common lithium-ion batteries, including lithium, cobalt, and nickel, are environmentally damaging to mine or rare and thus difficult to attain. See investigates elements such as calcium, magnesium, and zinc, which can do the job lithium ions perform inside batteries but are much more abundant in Earth's crust.

The challenge for See is that all these battery chemistries are nascent compared to the more mature lithium-ion battery, and therefore much of her work requires a search for stable ways to build batteries from these materials.

"There are materials that theoretically would be better than lithium-ion, or at least on par with it, for all of those elements," See says. "But we're not there yet."

It is worth the effort, however, See notes, since getting there will open the possibility of making more sustainable batteries to not only power smartphones and EVs but also to balance the smart grid.

## The price of power

Flip the switch, the light comes on. Pump a few gallons of gas and your car's ready to go. The seamless reliability of America's energy system has sheltered all of us from having to think about how it actually works. People tend to think about energy only when the power goes out or the cost of gas climbs too high.

If society transitions to a smart grid, Wierman says, a grid powered by renewables could be just as invisibly reliable as the fossil-fuel-powered system we have enjoyed to date. Still, citizens will inevitably become more attuned to the "whens" and "hows" of their energy use. This will happen most visibly through what Wierman calls "price signals." The cost of energy will move up or down over time depending on energy supply and demand; this will provide individuals with financial incentives to change their energy use.

"I do think that with a smart grid, price signals are going to be increasingly visible to consumers, especially for those with EVs," Wierman says. "The time of day you charge will be a significant factor in how much you pay for that charge, whether you're at home or in a parking garage. It's going to be something that may be frustrating for some but maybe exciting for others in terms of chasing the deal."

Indeed, Wierman says, some of the biggest hurdles to achieving a smart grid are not technological but sociological. The public needs both to overhaul the way it thinks about energy and to summon the political and economic capital to commit to infrastructure improvements to make the grid smarter and safer.

"I think that's a challenge that you often face in investing in sustainability as a society," he says. "The biggest investments, like installing and managing large-scale storage in the grid and doing that effectively, are not going to be things people see in their daily lives, except that there will be fewer power outages because of it. It will make the grid more sustainable."

And, with the help of Caltech scientists and engineers, smarter as well. [C]

**Julia R. Greer** is the Ruben F. and Donna Mettler Professor of Materials Science, Mechanics and Medical Engineering. She also serves as Fletcher Jones Foundation Director of the Kavli Nanoscience Institute. Her work on architected nanomaterials is funded by the Department of Defense and the Department of Energy.

**Steven Low** is the Frank J. Gilloon Professor of Computing and Mathematical Sciences and Electrical Engineering. His work on electric-vehicle charging and smart-grid infrastructure is funded by the National Science Foundation, Advanced Research Projects Agency–Energy, Department of Energy, Resnick Sustainability Institute, Defense Threat Reduction Agency, Southern California Edison, and PowerFlex Systems Inc.

**Kimberly See** is an assistant professor of chemistry. Her work on battery technology is funded by the Arnold and Mabel Beckman Foundation, David and Lucile Packard Foundation, National Science Foundation, Department of Energy Office of Science, Resnick Sustainability Institute, JPL, and Office of Naval Research.

**Adam Wierman** is a professor of computing and mathematical sciences and director of the Caltech Information Science and Technology (IST) initiative. His smart-grid research is funded by the Resnick Sustainability Institute, Center for Autonomous Systems and Technologies, Ronald and Maxine Linde Institute of Economic and Management Sciences, IST, National Science Foundation, VMWare Inc., and Beyond Limits Inc.

# Math for the Masses

**Po-Shen Loh (BS ’04)** thrives on interacting with people. Now he has created an app to keep them apart during a pandemic.

By Omar Shamout

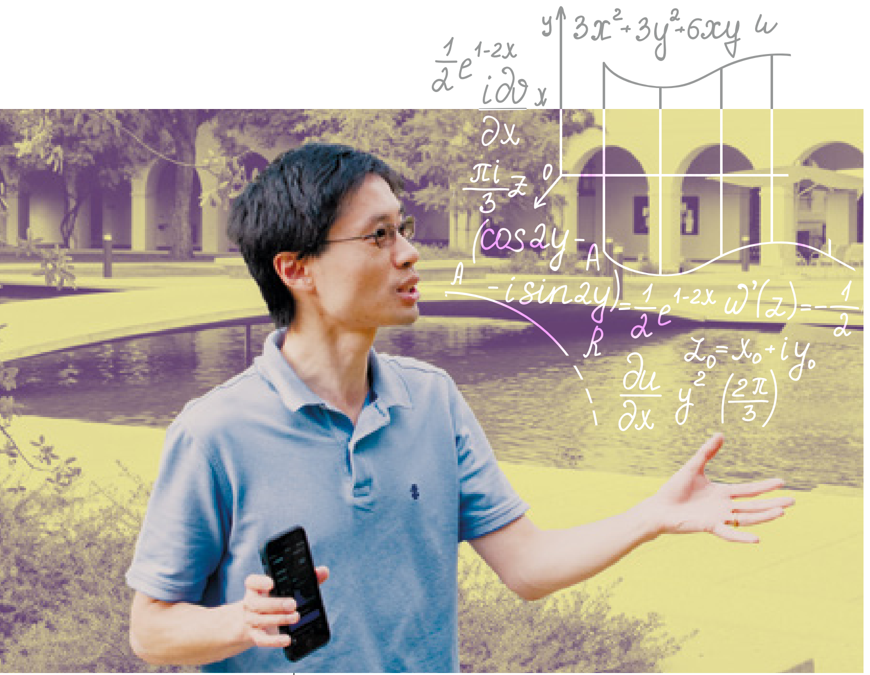
Consider it a proof of sorts. If you spend any time with mathematician Po-Shen Loh (BS ’04), you will find either that people will flock to him or that he will flock to people. This proved true on an evening in November 2021, when a throng of Caltech undergraduates became aware of his presence at the Red Door Café and stopped to listen in on our interview.

“I love people. I’m a people person,” says Loh, who had spoken to middle and high school students in Irvine and Monterey Park the day before his visit to Caltech. “I go all over the place because I’m trying to share ideas, and then other people share those ideas.”

A mathematics professor at Carnegie Mellon University, Loh is also the founder of the math-learning website Expii.com, the coach of the U.S. International Math Olympiad team, and a math evangelist who travels the country encouraging young students to think about math in new ways, including the method he invented to solve quadratic equations that eliminates the guess-and-check process from factorization.

“I have certain ideas of how I think things could be done better,” Loh says.

His omnipresence online as well as in person at schools and math competitions has made Loh a celebrity among math enthusiasts. When asked how they had heard of him, the Caltech undergrads could not recall how they first came across his name, only that it had seemingly always been a part of their lexicon. “It’s Professor Po-Shen Loh,” said one, implying it would be odd to suggest anyone had *not* heard of Loh. The Madison, Wisconsin, native



sat a few feet away, smiling his signature toothy grin and wearing his trademark shorts, part of the fall-and-winter uniform he had resolved as a Caltech first-year student to wear because he could never do so in his frigid hometown.

## Applying himself

Loh is an expert in combinatorics, a field of mathematics concerned with enumeration, or counting, within discrete systems, which have a finite number of states. Combinatorics overlaps with graph theory, another of Loh's research areas, which uses graphs made up of points to illustrate the relationship between objects or, in the case of Loh's most recent project, people.

While his teaching philosophy is based on reaching as many individuals as possible, he is now focused on keeping them apart. In March 2020, Loh and other Hertz Foundation Fellows were encouraged in a letter from a senior member of the organization's community to put their expertise to use in fighting the COVID-19 pandemic. (Loh was awarded a Hertz Fellowship, which recognizes "the nation's most promising graduate students in science and technology," in 2004.)

Hertz Fellows make a moral commitment to put their skills to work in times of national emergency even after their five years of funding are up. The day after receiving the letter, Loh was reading a PhD thesis on network theory from one of his students when its subject matter sparked a new train of thought. "I said, 'Oh, this is the first pandemic that we've had smartphones,'" Loh recalls, noting that smartphones are devices that are part of a network. "I realized there's room now to go and figure out the right way to use network theory and smartphones to help stop the virus from spreading."

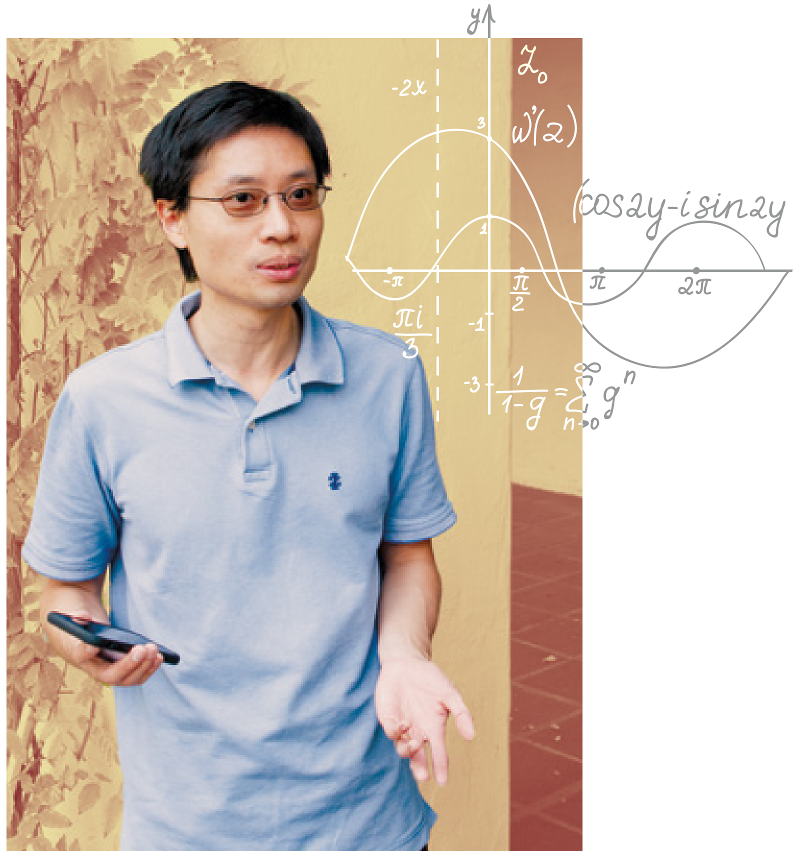
Loh decided to focus on the problem of contact tracing, and his solution, built with help from engineering and design students at Carnegie Mellon and others, is NOVID, an app that flips the traditional approach to contact tracing by helping individuals avoid infection rather than notifying them after they have been exposed.

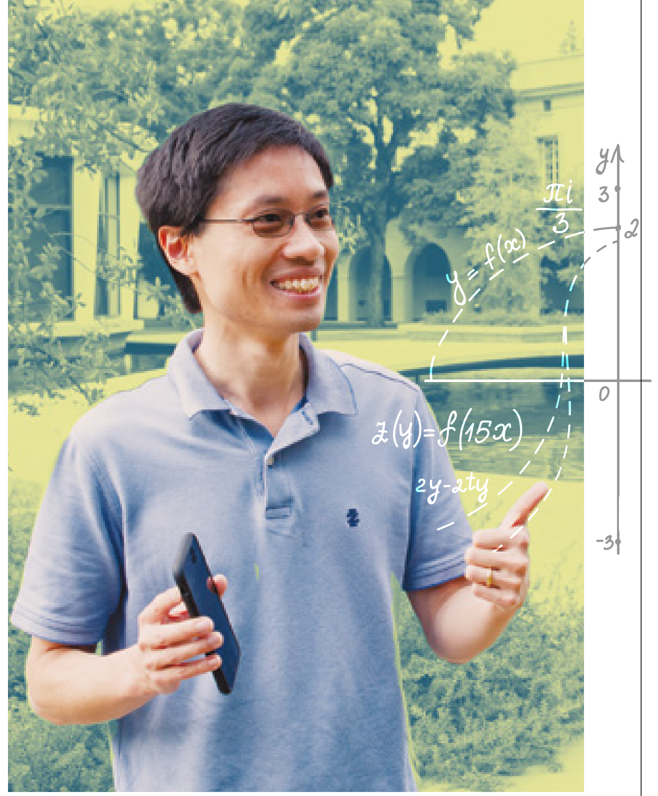
Using Bluetooth, ultrasound, and Wi-Fi technology, the app notifies a user when someone in their "network," which is based on all recent physical interactions across the entire user population, has been infected and, most importantly, how many relationships away the infected person is from the user. (For example, a "2" would indicate that the person infected is a frequent close physical contact of a frequent close physical contact.) The idea is to tap into people's instincts for self-preservation rather than implore them to act responsibly for the sake of others.

"Every contact tracing app in the world was designed to tell you after you've already been around someone sick. To tell you, 'Hey, now you're dangerous,'" Loh explains. "We said, 'Let's make an app that will tell you that somebody just got sick who spends time with someone who frequently spends time with you.' If you found that out, what would you do? Stay home."

Loh has met with public health experts who could help NOVID be deployed by various government entities in subsequent crises.

Shifting from a focus on pure mathematics to the type of applied math involved in the creation of the NOVID app, as Loh has done, can be tricky, says David Conlon, a professor of mathematics at Caltech who also specializes





in combinatorics and who first met Loh at the 1999 International Math Olympiad, where they were both competitors (Loh for the U.S. and Conlon for Ireland). The difficulty lies in applied math's focus on hard data.

"The impression is that math consists entirely of playing around with numbers, but if you're a pure mathematician that tends not to be the case," Conlon says. Pure math is more about theory than it is about computation and data, he notes. "But if you're interested in tracking COVID and seeing how quickly COVID spreads, that's a totally different thing. You really do need to do everything very quantitatively."

## Problem child

Loh has been experimenting in areas beyond pure math since his days at Caltech, driven by a relentless desire to find solutions to difficult problems. In fact, while he majored in math, he chose to do a senior thesis, which is not required of math majors, with a computer science professor.

"It's very rare," says David Wales, professor of mathematics, emeritus, who served as Loh's faculty adviser at Caltech, about Loh's decision to pursue a thesis at all, let alone in a subject outside his area of focus. "It's pretty amazing. It's an indication that he was really learning a lot in his major, but he had other things that he was interested in doing as well."

Loh not only delved into computer science academically while at Caltech but also competed on the three-person team that represented the Institute at the 2004 Association for Computing Machinery's International Collegiate Programming Contest in Prague in which he and his teammates placed seventh out of 3,150 teams from 75 different countries.

Why did Loh spend so much time on projects outside of math? He says that, in part, he was inspired by the creativity and ingenuity of the people around him. For example, Loh recalls the time one of his Caltech roommates planned to turn an ordinary bicycle into an electric-powered one.

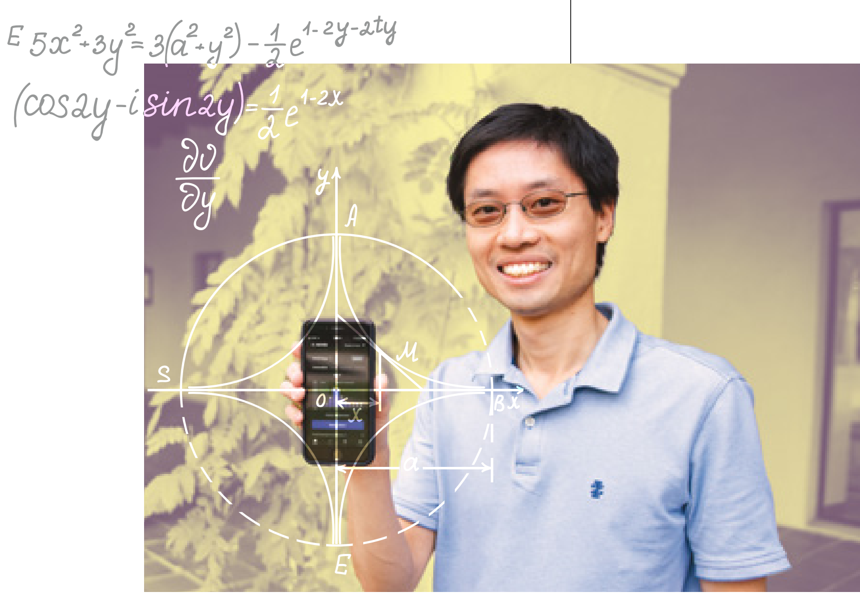
"People just did funny things," Loh says. "You had this feeling that, as a Caltech student, if there was an interesting, difficult, and quirky thing to do, you did it."

Loh's list of awards and honors during his time at Caltech is impressive by any measure. He won a Barry Goldwater Scholarship in 2003. He graduated top of his class in 2004. In addition to the Hertz fellowship, Loh received a Churchill Scholarship to study mathematics at the University of Cambridge; a National Science Foundation Graduate Research Fellowship; and a National Defense Science and Engineering Graduate Fellowship. After completing his master's degree at Cambridge in 2005, he received his PhD from Princeton University in 2010.

Caltech also became a family affair for the Lohs. His brother Po-Ru (BS '07) and sister Po-Ling (BS '09) are alumni as well, and he met his wife Debbie Lee (BS '04) on the first day of orientation.

Loh's years at the Institute helped him learn how to juggle a number of different projects at the same time. But his passion for figuring out new approaches to tough problems was born much earlier. When Loh was 11, his father, a professor of statistics at the University of Wisconsin, gave him a book of math puzzles that included a challenge to make four triangles out of six matchsticks.

"The answer is to make it 3-D," Loh says, recalling the problem that switched on that particular part of his brain. Since then, he has always tried to add new dimensions to his thinking. "If it is hard, and I think I might be able to do it, I'm going to try." [C]



# In Memoriam

To learn more about their lives and work, visit **magazine.caltech.edu/post/in-memoriam**.

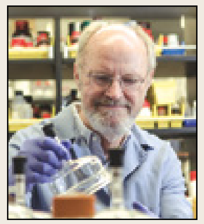
## James P. Quirk 1926–2020

James "Jim" P. Quirk, a former professor of economics at Caltech noted for his research into the economics of sports, died in June 2020. He was 93. In addition to his sports-related work, which included a paper he co-authored on the role of antitrust regulations in professional sports, he also authored economics papers on space station design, defense contracting, dams and reservoirs, boxing regulations, nuclear power, and capital gains. He was part of a group of Caltech professors that pushed for the creation of a PhD program in economics, which was established in 1972.

## Hugh P. Taylor Jr.

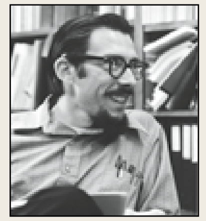
(BS '54, PhD '59) 1932–2021

Geochemist Hugh P. Taylor Jr., the Robert P. Sharp Professor of Geology, Emeritus, passed away on October 26, 2021. He was 88. He was one of a half-dozen scientists from Caltech who were selected by NASA to receive samples of lunar materials collected by Apollo 11 astronauts Neil Armstrong and Buzz Aldrin. Along with his graduate adviser, Samuel Epstein, Taylor searched the samples for isotopes of oxygen, hydrogen, carbon, and other elements to determine the temperatures at which moon minerals were formed and to discover any possible interactions between the rocks and water. His later isotope research led to a new understanding of hydrothermal convection on Earth and the effects of rainwater on basaltic intrusions.



## Robert H. Grubbs 1942–2021

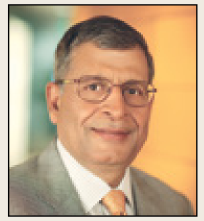
Robert Grubbs, the Victor and Elizabeth Atkins Professor of Chemistry at Caltech, passed away on December 19, 2021. He was 79. Grubbs was a co-winner of the 2005 Nobel Prize in Chemistry for the development of the metathesis method in organic synthesis. Metathesis is a catalyst-aided chemical reaction in which double bonds are broken and forged between carbon atoms in ways that cause atom groups to change places. Grubbs worked to develop powerful new "green" catalysts that helped make the creation of a host of products, ranging from new medicines to advanced materials, more sustainable. He also tackled issues affecting human health, including his work to aid the development of a new kind of replacement lens for patients with cataracts.



## James H. Strauss Jr.

(PhD '67) 1938–2021

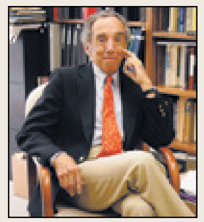
James "Jim" H. Strauss Jr., the Ethel Wilson Bowles and Robert Bowles Professor of Biology, Emeritus, passed away on December 28, 2021. He was 83. Strauss's research focused on the replication and assembly of two types of enveloped RNA viruses: alphaviruses and flaviviruses. These viruses include those that cause encephalitis, yellow fever, dengue fever, and other human diseases. Strauss served as executive officer for molecular and cellular biology from 1980 to 1989.



## Narendra K. Gupta (MS '70)

1948–2021

Narendra (Naren) K. Gupta, founder and managing director of Nexus Venture Partners in Menlo Park, California, and a senior member of the Caltech Board of Trustees, passed away on December 25, 2021. He was 73. In 2021, Gupta and his wife, Vinita, established the Naren and Vinita Gupta Fellows Program, which provides support for graduate students at Caltech, particularly those in the Division of Engineering and Applied Science. In 1980, Gupta co-founded Integrated Systems Inc. (ISI), an embedded software company. He was named a Distinguished Alumnus by the Caltech Alumni Association in 2004.

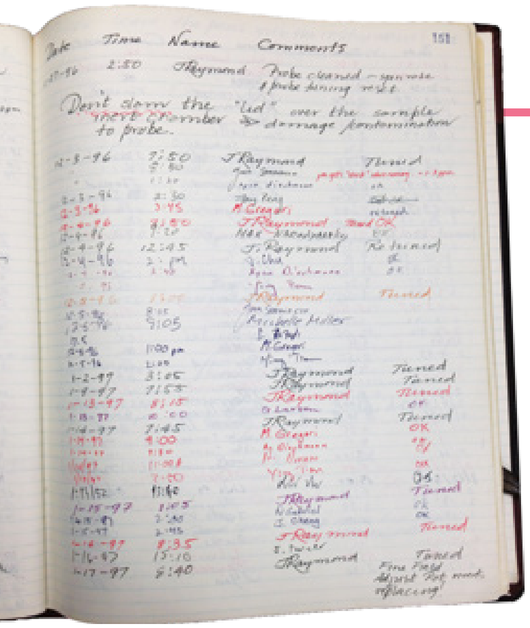


## Noel R. Corngold 1929–2022

Noel R. Corngold, professor of applied physics, emeritus, passed away on January 24, 2022. He was 93. As a nuclear engineer, he conducted theoretical work on how neutrons behave in reactors. When he transitioned to nuclear physics at Caltech, he dedicated himself to turning out physics students armed with a wide and deep knowledge of the field. Along with his dedication to teaching, Corngold continued with research in new areas related to transport theory and in particular to photons and charged particles.

# Endnotes

In recognition of the Clifford S. and Ruth A. Mead Memorial Undergraduate Chemistry Laboratory's demolition in November 2021 to make way for the Resnick Sustainability Center building project (see page 18), alumni were asked:



## What are your fondest memories of Mead and/or your undergraduate chemistry classes there?

As a chemistry major and a TA for Ch 3 and 4 … I must have run those old 90 MHz NMRs hundreds of times and logged my runs in the old lab notebooks assigned to each instrument. A few years ago, I got to drop by the lab and snap a few photos of the old log books with my entries and those of a few old classmates. … I really enjoyed my time in the lab: there was a certain camaraderie and friendly competition there. One time we got to run Prof. Grubbs' metathesis reaction to make little polymer sculptures. That stuff was absolutely indestructible!

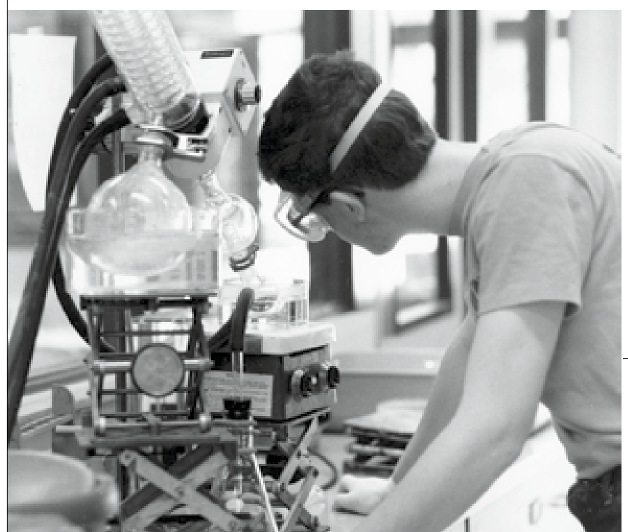
**Matt Gregori (BS '99)**
SAN JUAN CAPISTRANO, CA

Within the first half-hour of my first time in the freshman Chem 3 lab, I broke a test tube. At the time, it felt like a Caltech rite of passage. Looking back, it may have been an omen that "wet lab" science was not my calling.

**Sean McKenna (BS '17)**
TORONTO, ONTARIO

John Bercaw happening to walk by and witness me accidentally punching a hole through my flask with a glass rod.

**Erick Co (BS '95)**
HACIENDA HEIGHTS, CA



The first day of Ch 3 a, we were each given a list of equipment and tasked with ensuring our assigned drawers had everything. Many of us had no idea what a lot of the equipment was or what it was called. ("There's something called a 'cow'?")

**Theron Stanford (BS '87)**
JERSEY, CHANNEL ISLANDS

Mead Building housed the undergraduate student introductory chemistry laboratory, which had an MR spectral analyzer. It was run by a superbly kind and lovely lady. Although I remember it pained me to do laboratory chemistry since I was no good at it, she and others like her at Caltech (professors, postdocs, TA's, fellow students, staff) taught me to seek and do truth, and nothing less.

**Hsiu-Hsien (Tom) Ling (BS '89)**
CITY OF INDUSTRY, CA

I'm getting old. Things that weren't there when I was there aren't there now.

**David Turner (BS '61)**
LOS GATOS, CA

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And remember to get social:

Spilling the filter paper of Crac-Ac precipitate and having to sweep it up off the counter-top… my lab-partner was not happy with me at all! My TA let me pass the class if I wrote an essay about what I'd learned in chem lab, whew!

**Bruce Prickett (BS '82)**
ASTORIA, OR

For more Endnotes, go to
magazine.caltech.edu/post?tag=Endnotes

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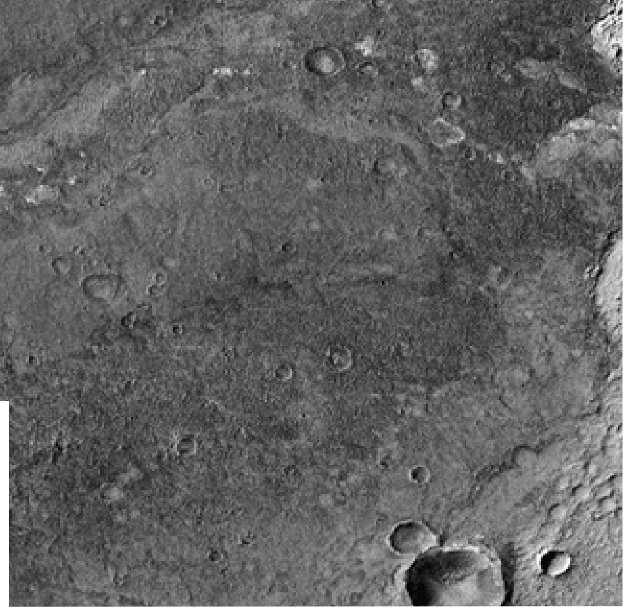
## Salty Clues to a Watery Mars

An analysis of large salt deposits on Mars indicates that ponds of liquid water persisted on the Red Planet for about a billion years longer than previously believed. Beginning in 2008, NASA's Mars Odyssey orbiter discovered hundreds of deposits of sodium chloride (table salt) stretching tens to hundreds of square kilometers in area. These deposits not only showed that Mars had been much wetter long ago than researchers had known, but also offered a way to determine the last time that water in liquid form had existed on the planet's surface. "Salt is incredibly soluble, so any moisture at all would dissolve it. These deposits must have formed during the evaporation of the last large-scale water on the planet," says Ellen Leask (PhD '20), who, as part of her doctoral studies, analyzed the deposits with Bethany Ehlmann, Caltech professor of planetary science. Leask and Ehlmann looked at what types of landforms the salt deposits formed on and how they were deposited across the terrain. They concluded the sodium chloride deposits formed as recently as 2.3 billion years ago. Previously, it was believed that large-scale liquid water on Mars ceased to exist around 3 billion years ago.



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