Summer 2022

Caltech magazine

Writing in the Language of Math

Contents

Features

Left: Some of Caltech's newest alumni reflect on their time on campus in advance of the Institute's 128th Commencement exercises on June 10. See **page 22** and **magazine.caltech.edu**

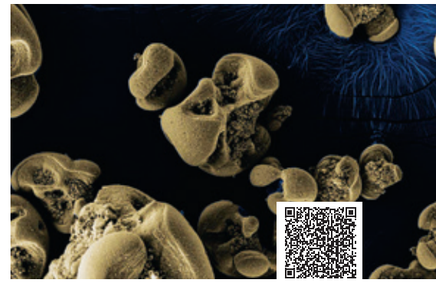
Departments

Online

Not just Ditch Day
Article: **The Traditions That Make Caltech**

Resnick Scholars speak
Learn more: **Why I study sustainability**

Meet the metal-eaters
Web extra: **The Power of Slow Science**



Visit **magazine.caltech.edu**

Summer 2022 Volume LXXXV, Number 2

Caltech
magazine

EDITOR IN CHIEF
Lori Oliwenstein

SENIOR EDITOR
Omar Shamout

ART DIRECTOR
Jenny K. Somerville

MANAGING EDITOR
Sharon Kaplan

ONLINE EDITOR AND
SOCIAL MEDIA COORDINATOR
Andrew Moseman

CONTRIBUTING WRITERS
Whitney Clavin, Lori Dajose, Davin Malasarn, Andrew Moseman, Ann Motrunich, Jon Nalick, Katie Neith, Robert Perkins, Sabrina Pirzada, Omar Shamout, Emily Velasco

DESIGNER
Jenny K. Somerville

ONLINE DESIGNER
Dennis Lan

ILLUSTRATION, PHOTOGRAPHY, VIDEOGRAPHY
Lance Hayashida, Peter Holderness, Dennis Lan, Jenny K. Somerville

COPY EDITORS
Sharon Kaplan, Carolyn Waldron

PRODUCED BY CALTECH'S OFFICE OF STRATEGIC COMMUNICATIONS
Shayna Chabner,
Chief Communications Officer

Read *Caltech* magazine on the go at **magazine.caltech.edu**

Contact *Caltech* magazine at **magazine@caltech.edu**

Caltech magazine ISSN 2475-9570 (print)/ ISSN 2475-9589 (online) is published at Caltech, 1200 East California Boulevard, Pasadena, CA 91125.

Image credits: Shutterstock/ Marina Sun (equations): cover; Lance Hayashida: TOC (center, large and middle right); 3 (top left and right); 6, 7, 8 (all except top), 9 (top left, bottom right, bottom middle); 23-27, 31 (top), 34-37 (microbe illustrations), 40 (right), back cover; Courtesy of Caltech Archives: TOC (top right), 3 (bottom left), 39 (top left), 40 (top left), 41 (top); Hang Yu/Caltech: TOC (bottom right); Karl Klein: 2; Cameron Hummels: 4-5; Jenny K. Somerville: 8 (top), 9 (middle, bottom right); NASA: 9 (upper right); Dennis Lan: 10 (top), 17, 32; Shutterstock/mountain beetle: 10 (disco ball); Bill Youngblood: 10 (bottom); IQIM and PhD Comics: 11; Omar Shamout: 12; Shutterstock/Marina Sun: 14-15 (equations); Scs/Wikimedia: 15; Osama Shukir Muhammed Amin FRCP(Glasg), https://creativecommons.org/licenses/by-sa/4.0/deed.en: 16 (left); Albert Einstein Archives, Hebrew University: 16 (right); Mathilde Marcolli: 18, 19 (left); courtesy of Carl Feynman and Michelle Feynman: from Richard P. Feynman, 'The Principle of Least Action in Quantum Mechanics,' PhD diss., Princeton University, 1942: 19 (top right); Event Horizon Telescope Collaboration: 20; Mark McGinnis: 28-31 (illustrations); Peter Holderness: 33 (top), 36 (top); NASA/JPL-Caltech: 33 (bottom); Shutterstock/pukach: 37 (bottom); John Zich/ University of Chicago: 39 (middle left); City of Hope: 39 (bottom left); Chris Flynn: 39 (top right); Family of David Evans: 39 (bottom right); Courtesy of Robin Wilson: 41 (bottom right).

Printed by Lithographix, Inc., Hawthorne, CA.

FSC label

Karl Klein, a control specialist with Caltech's Building Management Systems, snapped this photo of the Seeley G. Mudd Building of Geophysics and Planetary Science (South Mudd), which he posted to Instagram.

Letters

Putting Things in Perspective

That's a terrific photo on pgs. 4-5 of the spring *Caltech* magazine. BUT NO SCALE! How can I/we tell whether that's 6 inches or 6 feet?

Don Lewis (BS '56)
LAFAYETTE, CA

Editor's note: *We posed the question to the photographer, Mark Garcia, who said: "Since I was just working on the geobio course, I felt it was not necessary to use a scale bar since I was not doing any science. The area on the photo was probably 12 to 15 inches wide."*

Two Many Techers?

Received two copies of @CaltechMagazine today. Apparently someone else from @Caltech has lived in the same place before me....😅😂

Weilai Yu (PhD '21) on Twitter

A Fond Memory

Seeing the mention of the newly named Lee F. Browne Dining Hall in the Spring 2022 magazine struck a chord for me. It must have been in the summer of 1979 that, as a PhD candidate in chemistry, I was approached along with Bob Kreh by Lee Browne to see if we might be interested in providing about six weeks' instruction in chemistry to a group of incoming undergraduate students. The students were diverse in background, but had in common that they had attended schools where they had excelled but where the programs fell somewhat short of fully preparing them for Caltech classes. They also had in common being bright and enthusiastic learners. Bob and I developed our own condensed curriculum and enjoyed our time with these new students. Years later, I experienced an echo of that experience as director for 10 years of the NSF-funded Research Experience for Undergraduates at my research institution. Nice to see Lee being recognized!

Randy Morse (PhD '81)
ALBANY, NY

Kudos

All of your recent issues have been excellent, but today's was outstanding. And so far, I have only seen the articles about Po-Shen Loh, Ardem Patapoutian, and the video about magnets. Keep up the good work!

Neil Sheeley (BS '60, PhD '65)
ALEXANDRIA, VA

Caltech students attempt to solve a puzzle on **Ditch Day**, which took place this year on May 20.

Endnotes Sneak Peek

What do you remember most about your Caltech commencement day?

IT RAINED. We had a friend who attended about 35 Caltech graduations in a row, and we got to attend with him for about the last 10 before his death. Every time we'd sit with him, he'd say, "Hey, did you know that I've only ever been to one graduation where it rained? The sky just opened up, and everybody just scattered." And every time, I'd say, "Yes. That was my graduation." I think he really enjoyed bringing that up.

Donnie Pinkston (BS '98)
MONROVIA, CA

For more commencement memories, see Endnotes on **page 40**.

SoCaltech

- Commencement returns to Beckman Mall
- CE10 plots an ambitious sustainability roadmap
- A superposition snapshot; and more

A Lonely Off-Road

Up until this year, no one had ever hiked the entirety of Death Valley National Park from north to south in less than a week. In February, however, Caltech postdoctoral fellow Cameron Hummels covered the 170-mile route in four days—with six minutes to spare.

Death Valley, one of the hottest, driest, and least hospitable places in the world, is an unusual setting for a long-distance backpacking trip. But Hummels, a senior postdoctoral scholar in theoretical astrophysics, is part of the Fastest Known Time (FKT) movement, in which outdoor adventurers seek to traverse remote and difficult terrain as quickly as possible. Their efforts are authenticated using GPS records on exercise-tracking websites like Strava, leading to fierce but friendly competition with other athletes.

Hummels, abiding by the official FKT rules, traveled solo and unsupported, did not follow any trails or roads, and carried all of his food and equipment on his back. For water, Hummels relied on a few natural springs and seeps, some little more than mud puddles, which he had identified along the route and tested as part of his two-year preparation. Over the course of these four days in Death Valley, he experienced 60 mph winds, a haboob (an airborne wall of sand), temperatures higher than 100 degrees Fahrenheit, a salt swamp, arsenic- and uranium-laden water sources, a poisonous gas vent, and devastating fatigue resulting in visual, auditory, and olfactory hallucinations.

Why would anyone do this? “I think it makes the highs higher to have the lows lower, but it hurt a lot and was probably one of the hardest things I’ve ever put my body and mind through,” Hummels said. “It made for quite an adventure, but I hope to never do it again.”

CE10: Roadmap to Reduction

The Caltech Energy 10 project (CE10) is working to define the ambitious but achievable solutions needed to cut U.S. global warming gas emissions in half by the end of the decade. The CE10 public program, which took place on June 14 and 15, included livestreamed talks from Steven Chu, former U.S. secretary of energy; Sally Benson, current White House deputy director for energy; Kristen Siemen, chief sustainability officer at General Motors; and other experts in the energy and government sectors. The CE10 workshops on June 15 and 16 brought together key leaders to create a strategic roadmap for reducing global warming gas emissions that can realistically enlist broad public support.

“If you’re really optimizing economy-wide, you’re better off allowing that little bit of carbon to remain at the wholesale level and instead investing those dollars in reducing carbon emissions that may have a bigger impact in other sectors.”

Caltech trustee Pedro J. Pizarro (PhD ’94)
President and CEO of Edison International, speaking at CE10

For more information, visit: **ce10.caltech.edu**

Thanks to the Boss

Jean Somalwar, a graduate student in astronomy at Caltech, studies the stars in our galaxy and beyond. But she points to a different kind of star as one of her main inspirations: Bruce Springsteen. In fact, she says, the musician is the reason she got into college. A New Jersey native like the Boss, she has attended five Springsteen concerts (including three of his Broadway performances in New York) and has been a fan since she was 14. Somalwar even wrote her college application essay to Princeton University about meeting Springsteen at a 2016 book signing for his autobiography *Born to Run*.

“When I heard the emotional howls at the beginning of ‘Something in the Night,’ I had to stop working and just listen,” the essay reads. “Every line reflected my exact feelings, and for five minutes and fourteen seconds, the world disappeared.”

Somalwar began to collect Springsteen-related memorabilia when she was 16. The items, which include newspapers, magazines, concert tickets, and a poster, now fill up most of a wall in her home. “I’m under the impression that such displays are quite common among Springsteen fans,” she says.

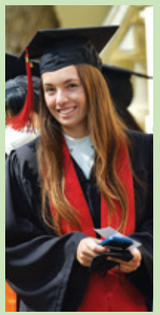
A Human Wave
In quantum superposition, subatomic particles can act like waves and occupy many places at once—a little like how Caltech graduate student Piero Chiappina can be seen here performing every stage of a backflip at once. In reality, large, or macroscopic, objects like people cannot be in many places simultaneously, at least not without the help of photography. But researchers, including physicists like Chiappina, are working to scale up bizarre quantum effects such as superposition and entanglement so they can be used in quantum computers and other future technologies. (See page 11 for more.)

A Day for Degrees

On Friday, June 10, 2022, Caltech held its 128th Commencement with a ceremony on campus, marking the first in-person commencement since 2019. Hundreds of graduates processed in front of a crowd of cheering friends and family on Beckman Mall. The Institute honored graduates with **560** degrees: **218** bachelor's degrees, **139** master's degrees, and **203** doctoral degrees.

Additional commencement photos can be found on Caltech's Instagram and Flickr accounts.

Watch a recording of the ceremony here:



History in Space

Jessica Watkins, formerly a Chair's Postdoctoral Scholar in the Division of Geological and Planetary Sciences (GPS) and a California Alliance for Graduate Education and the Professoriate (AGEP) Fellow, launched to space aboard a SpaceX Crew-4 mission from NASA's Kennedy Space Center on April 27, 2022. She then made history as the first Black woman to serve aboard the International Space Station, where her work involves making geological observations. Watkins received training from Lauren Edgar (MS '09, PhD '13), now a research geologist at the USGS Astrogeology Science Center.

Watkins spent two years working at Caltech on the Mars Science Laboratory mission's *Curiosity* rover with John Grotzinger, the Harold Brown Professor of Geology and Ted and Ginger Jenkins Leadership Chair for GPS. While a graduate student at UCLA, she worked at Caltech with Bethany Ehlmann, professor of planetary science and associate director of the Keck Institute for Space Studies. Both Grotzinger and Ehlmann traveled to Florida to wish Watkins good luck and watch the launch.

A New Hub for Math

Caltech trustee Richard N. Merkin, MD, founder and CEO of the Heritage Provider Network, will fund the Institute's new Richard N. Merkin Center for Pure and Applied Mathematics. As a hub for mathematical research on campus, the center will bridge disciplines and connect research in disparate areas that focus on the development of mathematical ideas and foundations in fields such as pure mathematics, computational biology, and quantum sciences.

Merkin and the Merkin Family Foundation have also provided funds to renovate the eighth floor of Caltech Hall. The reconfigured space, scheduled to open in early 2023, will provide a home for the Merkin Center as well as a base of operations for the American Institute of Mathematics (AIM), which will relocate from its current headquarters in San Jose, California. Sergei G. Gukov, Caltech's John D. MacArthur Professor of Theoretical Physics and Mathematics, has been named director of the Merkin Center. A member of the Caltech faculty since 2005, Gukov is known for important concepts relevant to string theory, quantum field theory, and pure mathematics.

Disco is Back

The Caltech student experience is unlike any other. From the House System to SURF to JPL, there is a lot for admitted students to consider and process as they make their decision about where to enroll as undergraduates. That is why the Caltech Undergraduate Admissions Office hosts Discover Caltech. The two-day event, also known as DiscoTech, made its return to campus in April 2022 alongside ecosySTEMs, a one-day pre-program that offers historically marginalized and underrepresented students the chance to experience the new community they will be joining.

Formally called the Pre-Frosh Experience, DiscoTech drew 433 attendees in 2022, including 222 who also joined ecosySTEMs. They heard from current students, faculty members, administrators, alumni, and others about not only Caltech's research, campus life, and commitment to diversity, but also what to expect after commencement. Nobel Laureate Frances H. Arnold, the Linus Pauling Professor of Chemical Engineering, Bioengineering and Biochemistry; and director of the Donna and Benjamin M. Rosen Bioengineering Center, welcomed the crowd with a keynote address about her lab's efforts to engineer enzymes using directed evolution.

EARTHQUAKE SCIENCE ON THE BIG SCREEN

For more than a century, Caltech's Seismological Laboratory has transformed society's understanding of earthquakes and geophysics through advanced instrumentation, data science, experimentation, engineering, and public outreach.

To celebrate the Seismo Lab's centennial, the Caltech Science Exchange, in collaboration with the Dr. Lucy Jones Center for Science and Society, will host a public event in Beckman Auditorium in November called "Shaking in our Seats: Earthquake Science on the Big Screen," to explores the science behind earthquakes in films such as 1974's *Earthquake* and 2015's *San Andreas.* Moderated by seismologist Lucy Jones, a panel of scientists, engineers, and disaster-response professionals will provide insight into what happens during and after earthquakes, how scientists and government officials interact, and the future of the field. Audience members will hear what Hollywood has done right and what it has done wrong, and will have the opportunity to ask questions.

The event is scheduled for ***Saturday, November 12,*** *at* ***1 p.m.***
For more information, visit: ***scienceexchange.caltech.edu/shaking***

Origins

The Institute for Quantum Information and Matter (IQIM)

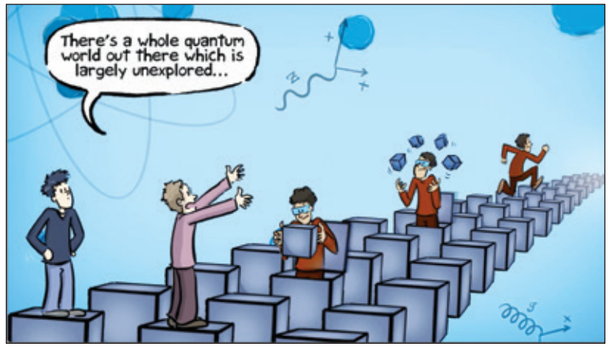
When John Preskill, now the Richard P. Feynman Professor of Theoretical Physics, came to Caltech in 1983, he planned to continue his work in particle physics and quantum field theory. By the mid-1990s, however, Preskill had switched his focus to a field that owes its existence to ideas posed by Nobel laureate and Caltech professor of physics Richard Feynman two decades earlier: quantum information theory. It was a career change that eventually led to the creation of what is now called the Institute for Quantum Information and Matter (IQIM), Caltech's long-standing home for cutting-edge quantum research.

Quantum information theory is the study of information processing on the quantum level. One of its primary aims is to guide the development of quantum computers, machines capable of far surpassing even classical supercomputers on certain problems of fundamental importance.

In the late 1990s, Preskill and H. J. "Jeff" Kimble, now the William L. Valentine Professor of Physics, Emeritus, received a grant from the Defense Advanced Research Projects Agency (DARPA), which was interested in quantum computing's potential applications in cryptography. Preskill and Kimble then hired Alexei Kitaev, now the Ronald and Maxine Linde Professor of Theoretical Physics and Mathematics, as a yearlong visitor.

Then, in 2000, Preskill and Kimble received a grant from the National Science Foundation, which they used to form the Institute for Quantum Information (IQI) that same year.

"NSF got a surge of funding for a program they called Information Technology Research, which included a lot of practical things, but also sort of a lunatic fringe of blue-sky research. And that's what we were part of," Preskill noted in an oral history for the American Institute of Physics conducted by science historian David Zierler, who now serves as director of the Caltech Heritage Project.



Guifre Vidal (Postdoc '01–'05), now a senior staff research scientist at Google, recalled those early days as a Caltech postdoc during a Heritage Project interview: "John had the vision ... to hire interesting young people for [IQI], then apply a hands-off approach. He's not the type of person who needs to control everything and everyone."

Liang Jiang (BS '04), a former IQI postdoc and current professor at the University of Chicago, told Zierler during a Heritage Project interview that weekly meetings were so full of discussion and questions that Preskill had to impose a time limit: "You could only talk for one minute because some group members would get really excited with the results and would talk a lot about their research."

By 2011, advances in quantum computing hardware, such as superconducting circuits and qubits (the quantum mechanical analogue of a classical bit), gave Preskill and Kimble the impetus to apply for more NSF funding as a means to broaden the IQI's scope to include experimental work. They received that funding and, in 2011, changed its name to the Institute for Quantum Information and Matter, for which Preskill serves as the Allen V. C. Davis and Lenabelle Davis Leadership Chair of the Institute for Quantum Science and Technology.

Spiros Michalakis, staff researcher and manager of outreach at IQIM, described this name change in a recent Heritage Project interview as a "visionary move," one that is still paying off: "We attach 'M'—matter—and it really mattered because … we started to have conversations with how you can implement certain things, and how you can convert some of the theories into experiments. … I didn't know many physicists or many people who were part of physics or even mathematical physics … who were not, basically, in one way or another, associated with IQIM. … If you look at the roster even now, for the second iteration of IQIM, the second cycle we have, there's a pretty cool medley of people."

Above: Still image from the 2013 video "Quantum Computers Animated" produced by IQIM in partnership with PhD Comics. The video features IQIM's **John Preskill** and **Spiros Michalakis.** Watch the video:

For more on the history of IQIM, visit:
magazine.caltech.edu/post/iqim-quantum-john-preskill

A Spotlight on STEM in Rural Areas

From left to right: Arjuna Subramanian, Elle Chimiak, Mike O'Connell, and Steven Bulfer at the 29 Palms Farmers Market.

On a sunny Saturday in April, in a stall sandwiched between lemonade and cotton candy stands at the 29 Palms Farmers Market, chemistry graduate student Andrea Stegner shows 10-year-old Kira Collins how copper film can be stretched, broken, and repaired thanks to the metal's atomic structure.

Since November 2021, Stegner and other Caltech grad students and postdocs have driven to the market on the first Saturday of nearly every month to showcase the wonders of science to the community. Unusual specimens from Caltech's extensive geology collection, such as augen gneiss and a meteorite, are often big hits in this 28,000-person rural community in the California desert. "Because of the area, people just love rocks," says Elle Chimiak (MS '19, PhD '21), a visitor in geochemistry, as scents from the Mine Train Smokery barbecue stall waft by. Nearby, the local junior high school concert band plays "Twinkle Twinkle Little Star." At a previous market, one mom even asked Chimiak if the group could come to her child's birthday party.

"I had to sadly decline," she says. "But I thought that was great."

Chimiak, who came up with the STEM Stall idea, works in the lab of John Eiler, the Robert P. Sharp Professor of Geology and Geochemistry. She receives some funding from the American Geophysical Union's Voices for Science program to cover gas and food expenses. While the science experiments wow the young visitors, the group has loftier aims.

"We want to let people know if you want to be a scientist, there is not one route to this, and you do not have to be a perfect student to get there," Chimiak says. As kids stop by to draw flowers and write their names on small sheets of copper film, the Caltech students also hand out postcards to adults that are addressed to area state and federal representatives, encouraging guests to ask their politicians for more broadband internet access and greater investment in STEM education.

"In rural areas like this, the broadband is terrible. We'll be your science Google. If you have a question we can't answer, we'll return next month with an answer," Chimiak says, wearing a tag that reads, "Ask me, I'm a scientist!"

According to a 2019 report from The Rural School and Community Trust, more than 9.3 million American students, or nearly one in five, attend a rural school. A particular focus of Chimiak and company's attention is the Rural STEM Education Act, which was passed by the U.S. House of Representatives in May 2021 and is now under consideration in the Senate. The legislation would provide research grants to fund teaching STEM in rural schools and fund broadband expansion.

Steven Bulfer, a grad student studying electrical engineering, has a personal connection to the group's mission having grown up on a farm in rural Minnesota.

"I didn't have a lot of science mentorship growing up, but I noticed when going to college that a lot of my colleagues had people who pushed them toward science," Bulfer says, noting he would like to help make kids aware of what science has to offer. "STEM was really quite a useful vector for me to do the things I'm doing today."

Sandy Smith, who has owned the Farmers Market with her husband Roger Thomas for four years, loves having members of the Caltech community come by.

"They're so patient, and they're good one-on-one with the kids and answering questions," Smith says. "Our kids need to know that these options are out there. We have a national park, but I don't think they realize, besides climbing on the rocks, what it all entails."

—Omar Shamout

Writing in the Language of Math

By Whitney Clavin

From chalk to software code, mathematicians and scientists use a variety of methods to express equations and formulas, and they have different ideas about the meaning behind their numerical prose.

In decades past, when researchers had to bang away at typewriters to write up their scientific papers, they would often hit a snag. The machines, including the IBM Selectric series popular from the 1960s to 1980s, did not contain keys for mathematical symbols, such as the long "S" used to represent integrals in calculus. When it was time to type in an equation, the researchers had to hunt for golf ball-sized silver spheres that contained the proper characters to snap into the typewriter. Some sought workarounds to avoid the hassle.

"I didn't have the patience to use the IBM Selectric and switch out the balls," says John Preskill, the Richard P. Feynman Professor of Theoretical Physics. "When I was an undergrad, I typed my senior thesis but left space for the equations and wrote them in by hand. For my PhD thesis, a technical typist typed out what I had written in longhand."

Today, typewriters have given way to personal computers and other modern technologies, making it easier for mathematicians and scientists to communicate their mathematical equations to collaborators and the rest of the world. Researchers share their formulas on virtual whiteboards, snap pictures of equations with their smartphones, and write out equations in documents using a much-heralded software program called LaTeX (pronounced lay-tech).

Across the Caltech campus, scientists and mathematicians have various methods for writing in the language of math. Some have gone digital, while others still prefer the gritty, tactile nature of chalkboards. Fernando Brandão, the Bren Professor of Theoretical Physics, says he has switched over to digital pens and pads

to write out equations. “I used to have equations written all over papers that were everywhere,” he says. “Now I save paper and trees.”

Not all researchers see these handwritten symbols and software codes the same way. Some call math the language of nature, while others describe it as a tool for abstract reasoning. Nevertheless, the researchers agree that mathematical notations allow them to reveal hidden patterns and structures in our world related to stock markets, computers, black holes, and even living beings.

“Math lets you encapsulate a lot of ideas at once. It lets you find incisive solutions that get to the heart of a problem,” says Tom Hutchcroft, professor of mathematics. “Imagine playing a game of chess and having to write a paragraph about each of your moves. This is what it would be like to do math without the equations.”

Ancient Arithmetic

The first written mathematical notations date back thousands of years and can be found carved into clay tablets, stones, and wood. The ancient Egyptians depicted numbers ordered in powers of 10 with symbols, or hieroglyphs, such as lotus flowers, fingers, and frogs.

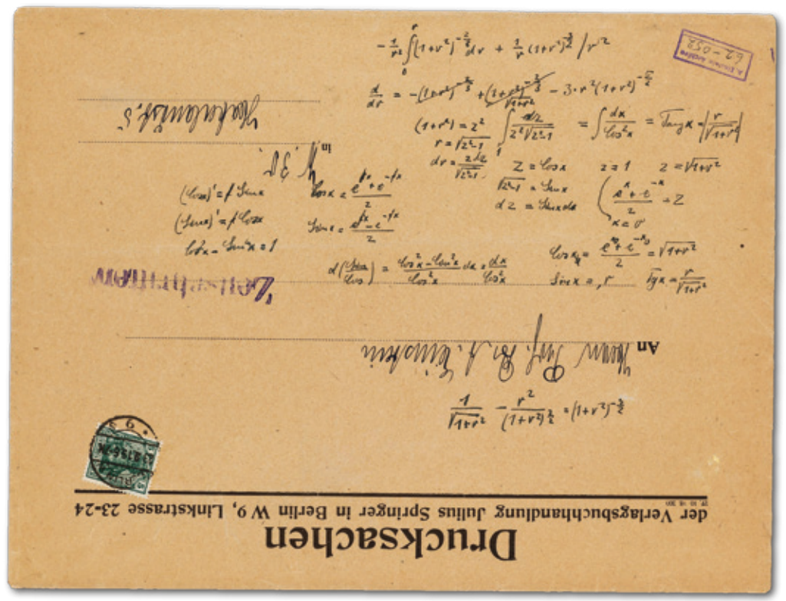
The modern mathematical symbols we know did not come into fashion until the Renaissance, which began in the 14th century. Before the symbols were introduced, the ancient Greek mathematician Archimedes, for example, derived the value of pi by using hexagons to approximate circles but did so without the use of the pi symbol, π, which was not introduced to represent the mathematical constant until the early 18th century.

As math progressed, so did the need for mathematicians and scientists to write down their equations. The advent of the typewriter in the 1870s made the job easier, but it was still a cumbersome task. In fact, many published papers, including those by Albert Einstein, who was a visiting professor at Caltech on three occasions, and longtime Caltech physics professor Richard Feynman, contain handwritten equations sandwiched between typed text.

Einstein actually wrote on the front and back of envelopes to carry out his calculations, explains Diana Kormos-Buchwald, Caltech’s Robert M. Abbey Professor of History and director of the Einstein Papers Project. That archive includes one such envelope from 1919 on which Einstein jotted down unidentified calculations. “This was a year after World War I ended, and there was a terrible paper shortage. People reused all paper before recycling was invented,” she says.

LaTeX Revolution

Preskill and other Caltech researchers recall the invention that finally relieved researchers of the burden of switching out typewriter balls.



Right: An envelope featuring handwritten calculations made by Albert Einstein in 1919. **Below:** A Babylonian clay tablet from c. 2000 BC with carved arithmetic tables.

Theoretical physicist Monica Jinwoo Kang enjoys writing equations on a blackboard with chalk made by the Korean brand Hagoromo.

Beginning in the late 1970s, Donald Knuth (PhD ’63) developed a typesetting language called TeX, which allowed researchers to more easily type out mathematical symbols. Leslie Lamport, a computer scientist then working at SRI International in Menlo Park, California, took TeX a step further to create the document-preparation system known as LaTeX, which uses the language of TeX. For example, to type the symbol π into a document, a researcher would write the command “π” into the LaTeX program.

“LaTeX has changed the way we communicate with each other,” says Professor of Theoretical Physics Xie Chen, who, like many other scientists, uses the TeX language to denote mathematical symbols when writing technical papers and even emails to colleagues. Sometimes, she says, they do not even bother to translate the codes back into mathematical symbols because the codes are so ingrained in their heads.

Smartphones have also changed the ways scientists communicate math; it is easy to snap pictures and send photos of formulas to one another. Virtual whiteboards have become more popular too, says Sergei Gukov, the John D. MacArthur Professor of Theoretical Physics and Mathematics. Gukov and many other researchers took part in online math communities during the pandemic that allowed them to connect with one another virtually in classroom-like settings and tackle various math and science problems. These communities were developed by the National Science Foundation–funded American Institute of Mathematics, or AIM, which will move its headquarters to Caltech in 2023. “The virtual whiteboards were key to these online communities and felt very much like real blackboards,” Gukov says.

The rise in popularity of videoconferencing has added yet another tool for mathematicians to communicate with one another, Preskill says: “Sometimes on Zoom, you just write an equation on paper and hold it up to the camera.”

Analog Beauty

Even with the advent of new communication tools, some researchers prefer to go old school. Monica Jinwoo Kang, Sherman Fairchild Postdoctoral Scholar Research Associate in Theoretical Physics, says she loves to write equations on her blackboard. “The fact that the blackboard is so big helps me think more clearly,” she says. She even has a favorite chalk: a Korean brand called Hagoromo.

“The difference between other chalks and Hagoromo is striking: the grip, the feel, and the effectiveness,” she

says. “The chalk is a bit thicker and holds amazingly while preventing any scraping sounds on blackboards. Also, the chalks write effortlessly without applying much pressure or force and without making a mess.”

Matilde Marcolli, the Robert F. Christy Professor of Mathematics and Computing and Mathematical Sciences, likes to create colorful watercolor pictures by painting over her equations. The creative process helps her focus on her mathematical research, she says. “It’s a kind of meditation, in a sense, where you are looking at the calculations you just wrote and thinking them over; the process of painting helps in formulating connections in the mind. It’s like a form of synesthesia, where mathematical thoughts come with colors and shapes attached to them.”

Rich Abbott, an engineer for the Laser-Interferometer Gravitational-wave Observatory (LIGO), has a similar affinity for handwritten equations, and he always writes them by hand on official engineering documents. “It’s beautiful to see the equations written out,” he says. “They are more human and compelling that way. You want to understand them.”

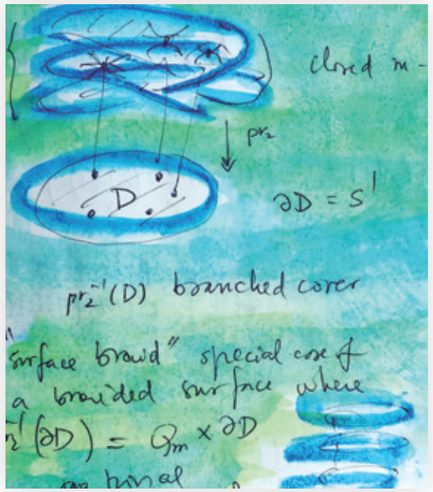
A New Lexicon

Math can be communicated in words too. When Archimedes explained to his peers how he calculated the value of pi, he did not have a language of mathematical notations to pull from. Instead, he used pictures and words. “It’s hard for me to fathom how Archimedes did that,” Hutchcroft says. “It’s one thing to have a personal understanding of how you think things work but quite another to explain your ideas to people.”

Today, words are still a key part of mathematical research. Omer Tamuz, professor of economics and mathematics, is intrigued by the words people invent to explain math.

“Math is more than equations,” he says. “Instead of writing ‘x=0,’ you can write ‘x vanishes.’ Thousands of words are invented to represent objects or functions in math. Sometimes, the invented words are clever and help you remember the meaning.”

Consider the word “matroid,” Tamuz says. A matroid is similar to a mathematical object called a matrix and ties together different concepts such as vectors and graphs. “Somebody made up this silly word, but it’s useful because you remember it, and it makes sense,” he says. “Pointless topology” is another math term Tamuz likes because it’s a “good play on words.” Pointless topology refers to a way of thinking about the properties of a geometric object without points, he says, adding that he considers it humorous to label an invented math concept as “pointless.”

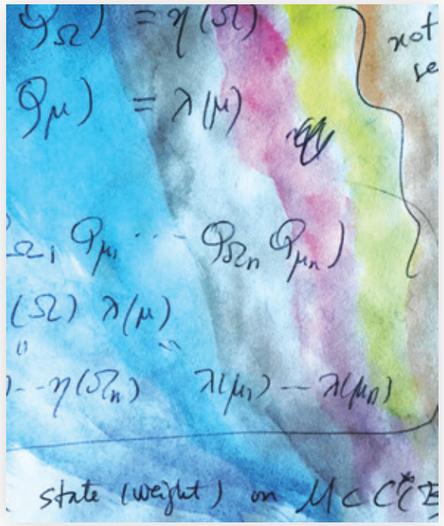


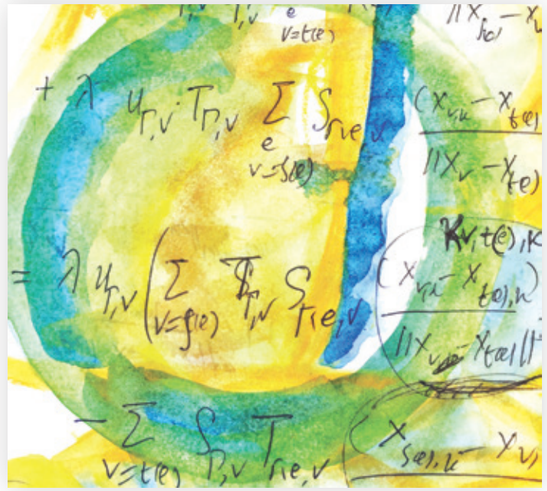
Right: Watercolor paintings by mathematician Matilde Marcolli that feature her written equations.

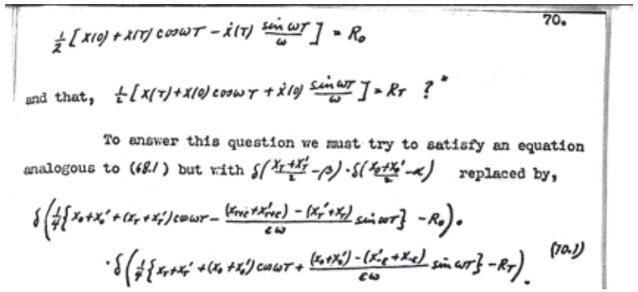
What Does Math Mean?

If math can be expressed in words, what does this say about the true nature of math? Are mathematical symbols merely human inventions used for expressing abstract ideas, or are they part of a fundamental language of the universe that exists independently of us?

Christopher Hitchcock, the J. O. and Juliette Koepfli Professor of Philosophy, says there are two main camps when it comes to the meaning of math and numbers. The first group follows ideas put forth by the ancient Greek philosopher Plato, who believed mathematical objects are real and possess identities that exist beyond ourselves.







Above: Richard Feynman hand-wrote equations in his 1942 PhD thesis at Princeton.

“Plato thought that mathematical truths would be true even if we didn’t exist,” explains Hitchcock. “Think of a line in geometry that is infinitely straight and perfectly thin. It’s not a physical object: there is nothing in our world that is like this. But it still has an existence independent of us. Another way to think of this is to ask: If there are an odd number of trees in the forest and nobody is there to count them, is the number still odd? Plato would say yes.”

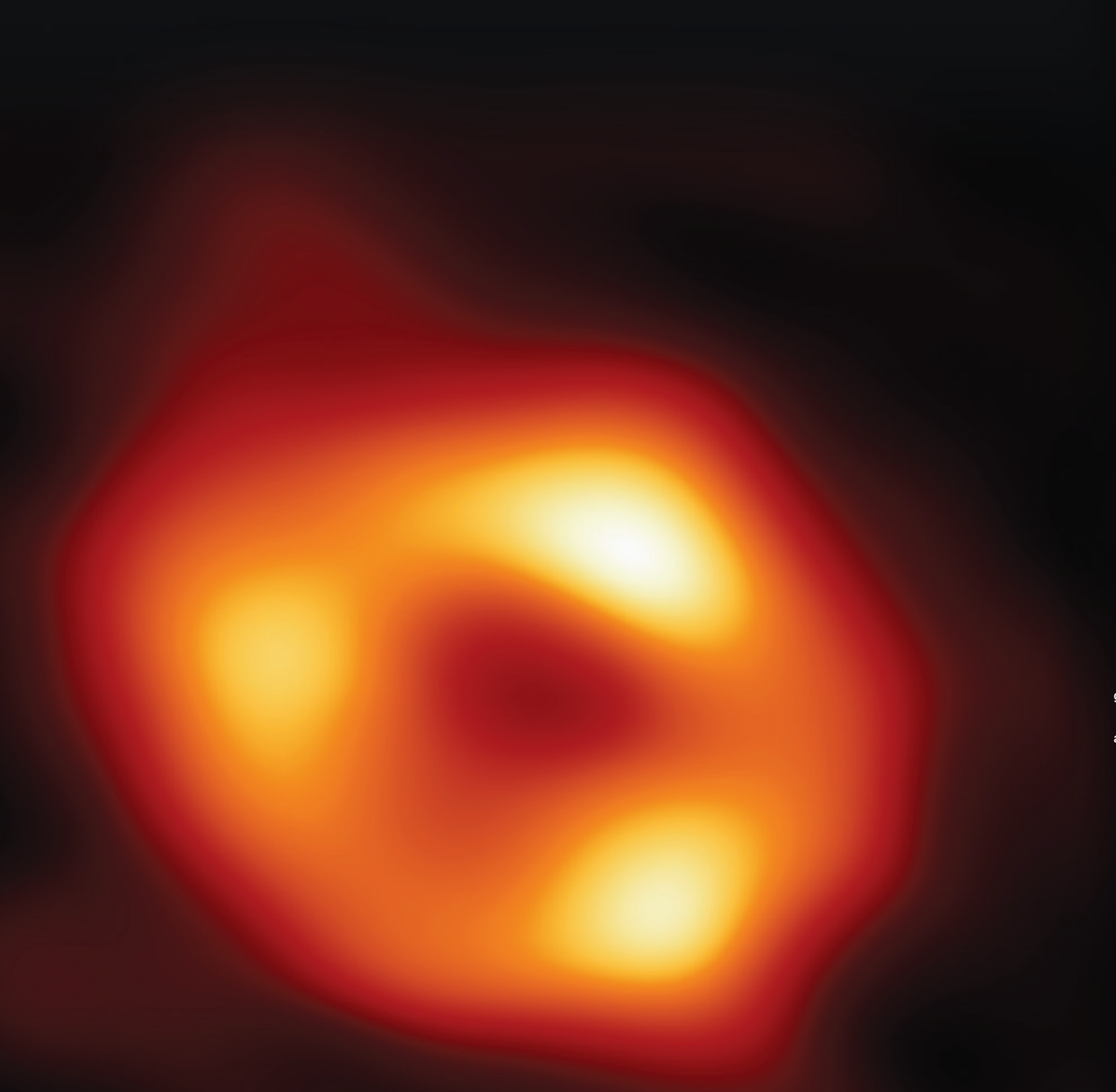
Many scientists agree with this Platonic view. Physicists in particular often describe math as the language of nature. Feynman, the late Nobel laureate who taught physics at Caltech for nearly four decades until his death in 1988, said in a lecture at Cornell University in 1964: “To those who do not know mathematics, it is difficult to get across a real feeling as to the beauty, the deepest beauty, of nature. … If you want to learn about nature, to appreciate nature, it is necessary to understand the language she speaks in.”

But as Hitchcock explains, other philosophers believe math is merely an invented tool of science and not an inherent part of our reality. Hartry Field of New York University has gone so far as to reformulate Newtonian mechanics without references to numbers. Field argues the structures described by math are fictitious and not literally true. To understand this viewpoint, Hitchcock gives the example of three plates on a table. It is possible, he says, to describe the plates without using the number three. You might describe each plate and point out that they are different from one another. In a similar way, you could say that each plate has six cookies. You could use multiplication to figure out there are a total of 18 cookies, but you could also derive a sentence describing each cookie and say they are different from one another without using the number 18. Exercises like this, he says, are meant to illustrate that math is simply a tool.

“You can use logical reasoning to explain things without numbers,” Hitchcock says. “But as the numbers get higher this becomes increasingly difficult. The numbers make the calculations much simpler.” Hitchcock himself believes in a more Platonic view of numbers. They are real, he says, but “in their own peculiar way.”

Whether or not numbers and math are real may remain an open question, but one thing is clear: mathematical writings scribbled on papers, digital pads, and coded in LaTeX continue to elucidate the wonders of our world.

Rob Phillips, the Fred and Nancy Morris Professor of Biophysics, Biology, and Physics, recalled in an article from the Summer 2021 issue of *Caltech* magazine that one of his grad school teachers had a blackboard on his door and used to tell him that if he had something to say, he should write it down in equations. “The language we speak in my lab is not English but math,” Phillips said.



A NICE Ring TO IT

By Robert Perkins

We now know what the supermassive black hole at the heart of our galaxy looks like thanks to Caltech researchers and their colleagues.

A multi-institution collaboration that includes a Caltech-led imaging team has generated the first image of the supermassive black hole at the center of the Milky Way galaxy. This result provides conclusive evidence that the body, known as Sagittarius A* (Sgr A*) is indeed a black hole and yields valuable clues about the workings of such massive objects, which are thought to reside at the center of most galaxies.

The Sgr A* image was produced by an international research team, called the Event Horizon Telescope (EHT) Collaboration, which includes more than 300 researchers from 80 institutions around the world. The result includes key contributions from an imaging team led by Caltech's Katie Bouman together with Kazunori Akiyama of MIT Haystack Observatory and José L. Gómez of The Institute of Astrophysics of Andalusia in Spain. Joining Bouman, who is an assistant professor of computing and mathematical sciences, electrical engineering and astronomy; a Rosenberg Scholar; and an investigator with the Heritage Medical Research Institute, were former Caltech postdoctoral researcher He Sun and current postdoctoral researchers Aviad Levis and Junhan Kim.

This is the second-ever image taken of a black hole. In 2019, the EHT collaboration released an image of a black hole named M87*, found at the center of the more distant Messier 87 galaxy.

Taking an image of Sgr A* at 27,000 light-years away from Earth is akin to taking a photo of a single grain of salt in New York City using a camera in Los Angeles. To accomplish this, EHT collected data from eight radio observatories scattered across the globe to form a single "Earth-sized" virtual telescope.

"This image from the Event Horizon Telescope required more than just snapping a picture from telescopes on high mountaintops. It is the product of both technically challenging telescope observations and innovative computational algorithms," Bouman said at a press conference announcing the new image. "Taking this picture of our black hole proved even more challenging than imaging the M87* black hole."

Although the black hole itself is completely dark, we can see a telltale ring of glowing gas surrounding a dark central region called a "shadow." The size of the shadow observed, which theory says depends primarily on the black hole mass, precisely matched the mass estimated by prior observations. The new view captures light bent by the powerful gravity of the black hole, which is 4 million times more massive than our sun. The team collected entire nights' worth of data over the course of multiple days, a bit like a traditional camera with a long exposure time. Members of the EHT went to the ends of the earth to collect these measurements; Caltech's Kim, for example, helped prepare a telescope near the South Pole.

Because the data came from only a small number of telescopes peering at an object far away, the EHT team was left with incomplete data to use to construct the image of Sgr A*. To reconstruct an image, they developed computational imaging algorithms that could make inferences to fill in the blanks.

"Through literally years of exhaustive tests on both real and synthetic data we are now confident that there is compelling evidence that the true underlying source has a ring structure," Bouman says.

Getting *personal*

New Caltech alumni discuss how their lives have changed due to the COVID-19 pandemic, and what was on their minds as they approached Caltech's first in-person commencement in three years.

In the best of times, a Caltech education requires an enormous amount of hard work, dedication, and resilience. But you would be hard pressed to find anyone who would describe the last two and a half years as the best of times. The COVID-19 pandemic brought new challenges to the lives and work of the Caltech community, and students at the Institute have handled these stressors in different ways. Here, some of Caltech's newest alumni reveal how they turned negative situations into opportunities for positive growth. They also talk about what it meant to endure a pandemic during their time at the Institute.

From left: Diego Olaya, Ayooluwa Odemuyiwa, and Ella Watkins-Dulaney

"I think the pandemic laid bare how important connections with other people are, and how important communities are. . ."

Katherine Rinaldi • PhD, chemistry

Rinaldi defended her PhD thesis in 2021, but is participating in this year's in-person commencement. She works at renewable-energy company H2U Technologies.

How has the pandemic impacted you?

It was hard, but I was lucky. I had done all my experimental work, and I was doing system-modeling work on my computer. As far as a direct impact on my work, it was pretty minimal. But doing a Zoom defense online was weird. From a personal-interaction standpoint, dealing with the pandemic was hard. And with so much going on in the world, it was hard to concentrate on my work. It was also hard to be separated from my family, who live on the East Coast. Trying to navigate how to maintain relationships and keep connections with people was a challenge. I think the pandemic laid bare how important connections with other people are, and how important communities are. I got involved with the Graduate Student Council's effort to get affordable health care for graduate students from Caltech. I learned how important it is to get organized. My experience at Caltech was made much brighter because of the other grad students and the people trying to make Caltech a better and more welcoming place for everyone.

What does it mean to you to have an in-person commencement?

That will be exciting because I didn't get the big celebration last year. My parents are coming, and my friends who have graduated over the last year are walking. It's going to be like a big party.

Diego Olaya • BS, physics

Olaya will pursue a graduate degree in physics at the University of Colorado at Boulder.

What effect has the pandemic had on you?

It feels like a lot of the seniors are making up for lost time this year. I'm trying to strengthen a few friendships that I'm hoping might last after I graduate. Many of my social interactions this year are partly colored by the fact that seniors are all going to graduate in relatively short order. To some degree, that means if I'm given the choice between taking an extra class that is somewhat interesting or leaving that space in my schedule for unstructured flexible time, I'm going to take the latter. Whereas, perhaps in more normal times, I would've taken the former.

What does it mean to you to have an in-person commencement?

Were we to graduate virtually, all of the traditions celebrating the achievements of the senior class and how each house sends off its seniors would have been gone. Things like Ditch Day, Interhouse, rotation, and even how the houses interact with prospective students when they come visit, are passed down from class to class by experience and repetition. For example, some houses have not had an Interhouse that anyone younger than us remembers. Our class is the only class currently on campus that has ever had an in-person Ditch Day. Those are extremely valuable parts of the Caltech experience that we came very close to losing. Thankfully, we didn't.

Isabell Yang • BS, biology

Yang will work as an EMT before applying to medical school.

What effect has the pandemic had on you?

Having more free time at home forced me to confront some mental health challenges that I had put off due to the rigor of Caltech studies. I am much better at understanding what I need to live a healthy and balanced lifestyle. I am kinder to myself and give myself the time to take a break without feeling guilty, and that helps me to be so much more productive. I already knew I wanted to go into health care, and I wished I could already be helping people out, especially when so many people were struggling.

Did you ever talk to anyone about what you were going through?

After my freshman year (in 2018), when I was going through those struggles, I was pretty transparent with my volleyball coach, Tom Gardner, because that was when I decided I was going to take a gap year. I said, "I really enjoy playing for Caltech, but I don't know if I can continue." He was really supportive. He wanted what was best for me, and it didn't seem like he only cared about the team. Since then, when I got back, we've been really close, and I was chosen to be a team captain. The other captains and I talk with him often about how the team is doing and what their energy and attitude is like. All of that made us really close.

What does it mean to you to have an in-person commencement?

In my freshman and sophomore years, I couldn't imagine finishing at Caltech. My focus wasn't on graduating, it was just on taking it one day at a time, one assignment at a time. I think I won't realize how big of a deal it is until I'm actually at the ceremony and receive my diploma.

Spencer Schneider • BS, computer science; business, economics, and management (double major)

Schneider will work at Meta as a software engineer.

What effect has the pandemic had on you?

It's made me a lot more reflective. I took a year off. I got to live on my own, work with the Washington Wizards as a software engineer, and get a taste of the adult world. It made me more appreciative of the unique things in college, like getting to wake up whenever you want and deciding to do your work whenever you want. In general, I'm trying to live in the moment and appreciate the situation I am in now because it can change at any moment. I'm OK doing my own thing a lot more, especially since the majority of my friends have graduated. I had a lot of time to figure out what I wanted to focus on when I came back to school. This past year, I took a lot of project courses because I feel they're relevant to the skills that I want to develop. I was more focused.

"I'm trying to live in the moment and appreciate the situation I am in now. . ."

Did you miss being around your basketball teammates?

A hundred percent. I tried to get virtual events going, to play *Among Us*, hop on Discord or Zoom, or watch a movie. But it's hard. Everyone has different schedules. People are in different time zones. I was the captain [of the basketball team], and I feel like I didn't do a great job of that. It's still something I think about. The coaches also reached out and tried to keep in touch. This past season, making the program better, getting to a point where we were a contender in our conference was really rewarding. I enjoyed going to practice every day—even the bad parts were a little more fun.

Ayooluwa Odemuyiwa

- BS, computer science

Odemuyiwa will work at Meta as a software engineer.

As ASCIT president in 2021–22, how did you help other students adjust not only to life at Caltech, but to life at Caltech during a pandemic?

There were a lot of first years enrolling without knowing anything about the school, and it was really hard to reach a lot of them. I was an FCC [frosh camp counselor] during orientation. I saw a lot of them burning out and not really feeling connected to the school. A big thing for me was trying to find ways to engage them, to make them feel connected, and make them feel like actual students. Some things we did were to make a first-year support committee, and we also connected them directly with upperclassmen by setting up lunches with them over Zoom.

What were your biggest challenges during your time at Caltech?

My first year at Caltech, I really struggled. First, because of my high school, my academic background wasn't as strong as some other students'. Second, I'm a Black student, and I struggled moving from an area where there were a lot more Black students and more Black people in the community. I struggled mentally with stress and depression, imposter syndrome, and also just navigating Caltech. I wouldn't ask for help, and I would try to prove to people that I knew everything when everyone else would be asking for help and working with others.

> "Once you acknowledge you don't know everything, you can do anything."

Were you able to find help on campus?

Yes, as part of the Freshman Summer Research Institute at Caltech, I connected with Monique Thomas and Taso Dimitriadis in the Caltech Center for Inclusion and Diversity (CCID) office. I reached out to Monique, who's a Black woman, and talked about my experiences and was very honest with her about how I was feeling. Lee Coleman [from the counseling center in Student Wellness Services] was also very helpful. He visited me and talked to my mom. Also, the deans, Kristin Weyman and Lesley Nye. They were very supportive when I had to take some time off for a couple weeks. The TAs and professors were accommodating during that time and helped me get on my feet. Understanding that school is hard and that I was going to struggle was my biggest realization that came from the first year. The support I received from faculty, staff, and others really taught me the importance of giving back to my community through leadership service, and I went on to serve as ASCIT president, in Ricketts House leadership, and with the Black Scientists and Engineers at Caltech.

Did you find a home here at Caltech?

Absolutely. Caltech has definitely trained me to be someone who's acutely aware of the importance of representation in STEM and also just the importance of understanding that you don't know everything. And once you acknowledge you don't know everything, you can do anything.

Shrikeshav Deshmukh

- BS, mechanical engineering
(minor in environmental science and engineering)

Deshmukh will work at SpaceX as a Starlink engineer.

Was there a moment that crystallized the gravity of the pandemic for you?

At the beginning of the pandemic, I was sitting in Browne Dining Hall having lunch. The TVs were flashing with all this information on COVID. I was one of the last people to leave campus, so it felt like a ghost town. That's when I realized, wow, this is the real deal. Later on, Caltech said we were not going to have fall term in person. I then realized this could go on much longer than we had originally thought.

What effect has the pandemic had on you?

I used to be on the track and field team, but COVID gave me time to consider if I really wanted to continue the sport that I had been doing for nearly a decade. It was a very difficult decision to leave, but it allowed me to pursue other opportunities that I'll only find at Caltech and allowed me to get more involved in project classes, robotics, and dance. Dance was just a hobby before, but since returning to campus, I've spent much more time on it and now lead the Dance Team. I've learned a lot of different styles and am even teaching my own classes, which I would not have imagined I'd do four years ago. After being off campus for so long, I really try to make the most of every moment I have left before I graduate.

> "After being off campus for so long, I really try to make the most of every moment I have left before I graduate."

What does it mean to you to have an in-person commencement?

In-person commencement drives home a feeling of accomplishment, marking the end of my chapter here at Caltech. It means a lot to me, as it cements the feeling that I'm transitioning from one era of my life to another.

Did the pandemic change the way you go about your research?

The nature of my research allowed me to make progress without having to go to the lab. Data collection using crowdsourcing platforms is a new trend in my field. It's much easier to reach a diverse sample of participants, and to get the data quicker. It comes with challenges as well. I had to monitor the studies and answer questions all day long, and to act fast and solve problems as they arose. For example, the site we used for recruitment became completely unusable at one point, and we had to manually provide study links to every single participant.

Was there a particular moment over the last two years that crystallized the gravity of the pandemic for you?

I come from China, so I was aware of the coronavirus earlier. I had planned to go back home and visit family for the Spring Festival in January 2020, which I always do. But I canceled the flight, knowing what was going on in Wuhan. At the time, I wasn't seriously concerned that it would become a global pandemic. But by March, I remember it was difficult to get masks. When we did get masks, it felt uncomfortable to wear them in public even though it was obviously the correct thing to do.

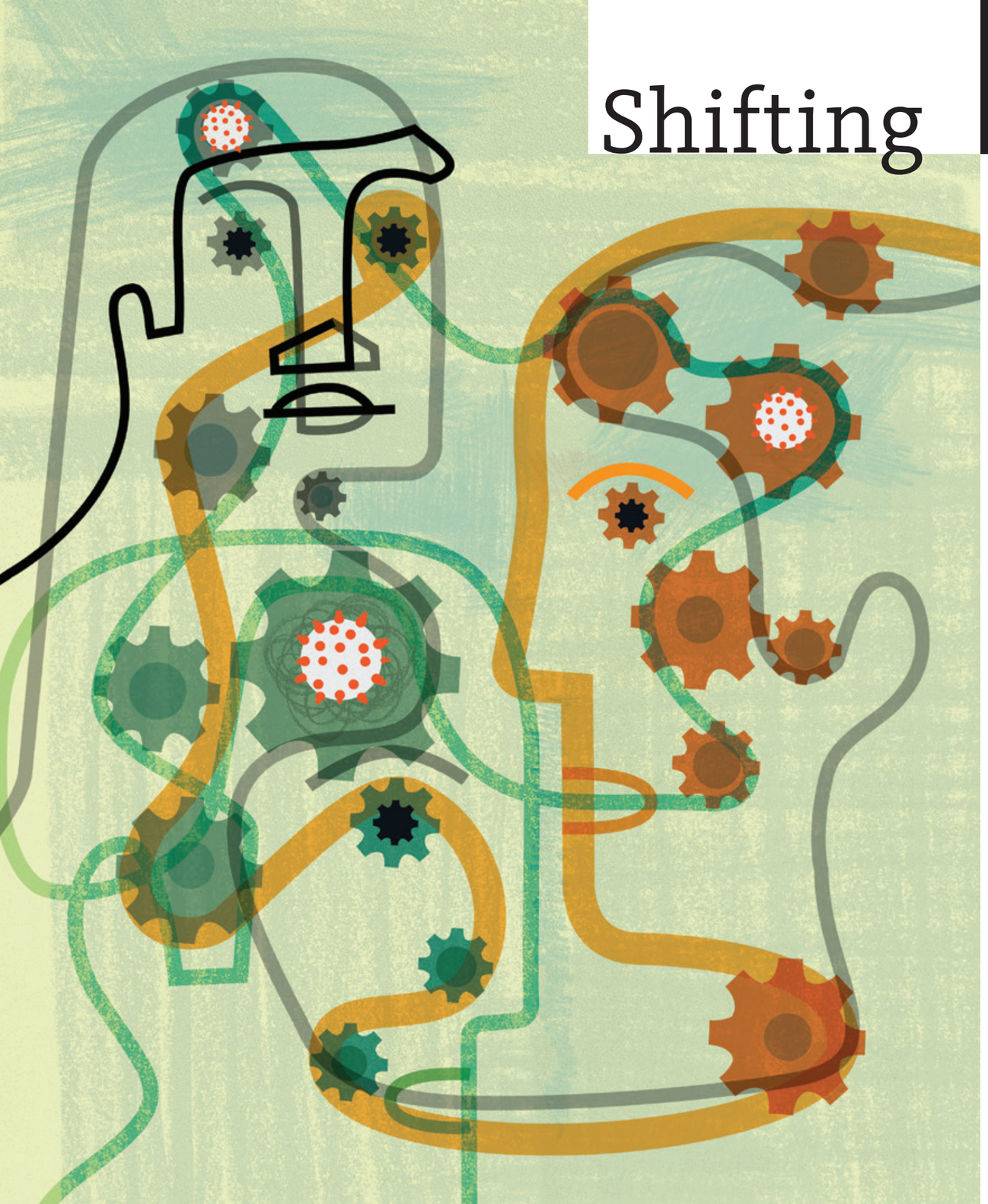
Yanting Han • PhD, neurobiology

Han will work as a postdoc in the lab of Ralph Adolphs (PhD '93), Bren Professor of Psychology, Neuroscience, and Biology at Caltech.

Did the pandemic alter the focus of your research?

The pandemic probably had a positive influence on my research rather than negative. I study human emotion experiences by evoking emotions using stories and videos, and collecting self-report ratings from participants. During the pandemic, I co-led the COVID-Dynamic Longitudinal Study, which tracks people's psychological changes during the pandemic in multiple domains, including emotion and mental health, decision-making, attitudes and beliefs, and so on. We realized that it would be nice to take advantage of the opportunity and sample naturally occurring emotions in people's daily lives in addition to the evoked ones. This allows us to study those emotions in comparison to the evoked ones and in the specific context of real-world events. Although this is still early stage exploration, we've already seen many interesting things. For instance, collectively, moral disgust went up for George Floyd's death, and surprise went up around Election Day.

To hear from more new alumni about their experiences, visit: **magazine.caltech.edu/post/new-alumni-2022**



Shifting Gears

The Fight Against COVID-19 Advances

By Katie Neith

Caltech researchers have helped stem the disease's spread since the early days of the pandemic. Their work is not yet done.

When aerosol expert Richard Flagan could not come to campus to investigate the effectiveness of masks at stopping transmission of the SARS-CoV-2 virus, he brought the work home with him: specifically, to his home garage and its collection of woodworking tools. That is just one of the many ways Caltech researchers had to adjust not only the work being performed in their labs, but also the manner in which that work took place after in-person operations nearly ground to a halt in early 2020. Since then, many more intrepid scientists, engineers, and students have sought to refocus their work to address the needs of the global health crisis, despite hardships like limited capacity rules, shortages in resources, and fear of an unknown and evolving virus.

Nearly two and a half years later, these scientists have made crucial contributions to both local and national efforts to control the spread of the SARS-CoV-2 virus. These life-saving advances were made possible thanks to new funding, more public health data, a greater understanding of the virus and its effects on society, and the desire of students to help. Here are some of the major developments that have taken place in labs across campus, the unique challenges they presented, and the rewards they delivered.

Safeguarding the Workplace

Flagan, an engineer and expert in aerosol processes, flew to Helsinki in February 2020 to participate in a workshop about atmospheric particle formation experiments at the European Organization for Nuclear Research (CERN).

"I was very nervous to travel," Flagan says. "I had been aware of COVID since the first press reports, and the descriptions sounded like an airborne disease transmission, but that was not the message that was being delivered."

By the time he returned to campus, Caltech was just days away from shutting down nearly all research. Exceptions were being made, however, for studies involving COVID-19. Initially, Flagan's laboratory was involved in a study of how the first major lockdowns affected air quality. Soon, concern arose about how to open laboratories again.

"The variability of mask effectiveness became one of the central questions," Flagan says.

Flush with state-of-the-art aerosol instruments in his laboratory, he realized that testing masks was a great match for his research group. There was just one problem: as a person over the age of 60, Flagan was up against the strong recommendation to avoid coming onto campus, even for critical projects.

Enter Buddhi Pushpawela, a postdoctoral researcher who had joined Flagan's team in November 2019. Alone in the lab, she set to work in June 2020 to build an experimental apparatus using whatever parts she could find, scouring campus for masks to test how effective they were at blocking the virus. But first, she needed to figure out how to seal the masks to the sampling instruments. In his home workshop, Flagan cut custom wood frames that Pushpawela used to clamp the masks to the plates.

"Whenever I had issues, I showed the setup to Professor Flagan through video calls and got his advice on how to do the modifications," says Pushpawela, now a clinical assistant professor of physics and astronomy at the University of Alabama in Huntsville. "I have the theoretical background and the subject knowledge, but I used some of the instruments for the first time for the face-mask testing project."

During the experiments, she measured particle penetration, breathing difficulty, and performance at different oxygen flow rates. It was a process that took nearly two hours to complete for each mask, but Pushpawela managed to test more than 400 samples, including N95s, KN95s, surgical masks, and cloth masks. Based on those results, Flagan and Pushpawela made recommendations

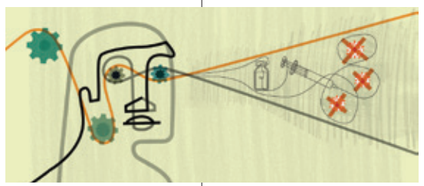
that guided Caltech's initial purchase of masks to help reopen campus widely for the 2021 fall semester. In addition, Flagan conducted webinars, presentations, and discussions on social media to inform the public about the effectiveness of various masks. The team published a paper with their findings in the journal *Aerosol Science and Technology* in December 2021.

"I believe we made a contribution to stopping the spread of COVID-19 and saving lives from COVID-19, at least among the Caltech community," Pushpawela says.

A Universal Vaccine?

Structural biologist Pamela Björkman is no stranger to viruses. She has dedicated her career to investigating the body's immune response to viral pathogens, and she had already received supplemental National Institutes of Health (NIH) funding to study the emerging SARS-CoV-2 virus by February 2020. But even with many similar studies under her belt, this undertaking felt different.

"Everybody knew that it was going to be very bad," Björkman says. "And running a lab was very confusing back then. We had density rules, we had to have shifts, and we had to constantly figure out who could work where and space people far apart. I was very worried that we would have an outbreak in the lab. We didn't, but I remember being very nervous about that."



Despite these stressors, the Björkman group has made significant progress in its goal to develop a universal vaccine against current and future coronaviruses.

First, Christopher Barnes, then a postdoctoral scholar in Björkman's lab and now an assistant professor of biology at Stanford, detailed the structures of antibodies produced by the body to fight COVID-19 and discovered how those antibodies bind to the virus's spike proteins (the parts that invade host cells) to stop the infection process. Barnes found that the antibodies attach to a part of the virus called the receptor-binding domain, or RBD. But not all the antibodies were binding at the same place on the RBD and the RBDs varied between the original SARS-CoV-2 virus and its newly emerging variants, as well as between related coronaviruses found in animals.

And so, Björkman says, "we did something we've been trying to do for HIV and other viruses in my lab for a long time. We made a nanoparticle that's a mosaic, meaning it co-displays different versions of the antibody target on the virus."

Alex Cohen (PhD '21), now a postdoctoral scholar in the Björkman group, designed a mosaic nanoparticle to present eight different RBDs on 60 attachment sites. Testing of the concept in animal models as a vaccine showed that the nanoparticle evokes strong immune responses to not only the viruses included in the vaccine, but also to additional coronaviruses not included in the vaccine.

Further testing has revealed the mosaic nanoparticle approach prompts antibodies to target harder-to-reach but more-conserved elements of the virus RBD, as opposed to the parts that may change with a new variant or type of coronavirus. This means the vaccine should provide broad protection regardless of how the virus mutates in the future or if new coronaviruses spill over from animals into humans, making it a strong candidate for a potent universal vaccine. The Björkman group has received funding from the Coalition for Epidemic Preparedness Initiative to conduct Phase 1 human clinical trials.

"This vaccine candidate can be used as a booster, since most people are already vaccinated or have been infected with SARS-CoV-2," Björkman explains. "It would be more protective, I believe, against possible future emerging viruses, and you wouldn't need to change it as we are confronted with more SARS-CoV-2 variants of concern."

Modeling Transmission

As the pandemic raged on and classes remained virtual, many students wanted to get involved in COVID-19 research. Yaser Abu-Mostafa (PhD '83), an expert in machine learning, decided to give students in his spring 2020 computer science class a project. The result was a model to predict the spread of the virus that consistently beat out estimates made by the Centers for Disease Control and Prevention (CDC).

"We switched the entire research and teaching effort to focus on forecasting the spread of COVID-19 in the United States," says Abu-Mostafa, who had been working on a fundamental theoretical question in deep learning prior to the pandemic. "The students are the ones who took the initiative, and I went for it based on my assessment of the value of artificial intelligence technology to help with what was clearly a national emergency."

The CDC model used data from 45 major models at universities and institutes across the country, but it did not emphasize artificial intelligence (AI), which has the power to discover patterns hidden in data that humans might miss. Early tests of Caltech's AI-driven CS156 model, named for the class where it began as a competition, showed it was more accurate than the CDC model nearly 60 percent of the time. Though it proved extremely valuable, Abu-Mostafa says it was not easy to accomplish.

"We needed to steer the whole ship in a completely new direction in short order," he explains. "This involved organizing the biggest team I have ever supervised, setting up the computational and data infrastructure, securing the

Aerosol expert **Richard Flagan** in his home garage, where he built frames used in tests to gauge the effectiveness of various masks against SARS-CoV-2.

funding, and, most importantly, formulating the scientific vision and the strategy to implement it successfully."

It started with a class of more than 150 students producing 40 viable models for predicting the spread of COVID-19. From there, the top 10 models were aggregated, and a research team that included a core group of students from the class took the findings forward to create a model with an expanded scope, making rapid and precise predictions about mortality rates, numbers of infections, and test positivity rates.

"In the early days of the pandemic there were massive data gaps and uncertainties in everything from case levels to rates of mask wearing," says graduate student Dominic Yurk (BS '17, MS '21), who was the lead teaching assistant for the course and continued as a member of the research team when the class ended. "Figuring out how to make valuable predictions from highly uncertain data was a new and valuable research experience."

Shortly after initial results of the model were made public in summer 2020, the California Department of Public Health asked for access to the team's daily prediction files, which informed the department's decision-making as it managed the pandemic.

"We expected to do well given our expertise in AI, but beating all the national models put together was a surprise," Abu-Mostafa says. "While I am used to taking scientific risks, this experience encouraged me to take organizational and funding risks that are against my nature, when the opportunity arises."

The COVID-19 model also inspired him to look at other medical problems that machine learning might help solve.

"It was my first experience in research that can, and likely did, save lives," Abu-Mostafa says. "I haven't done that before in my career, and the experience made me more energized in my current focus on medical applications of AI."

Measuring Viral Load

Viruses need hosts to replicate, but exactly when a person is contagious is not always easy to pinpoint, especially with a new pathogen.

"The world clearly didn't have information on how to detect SARS-CoV-2 early, before people transmit the infection," recalls chemical engineer Rustem F. Ismagilov about the early months of the pandemic. "It was not known how much virus there was and, therefore, what sort of test would be good enough to detect it, and in which sample types, like saliva or nasal mucus, the virus was."

With the interdisciplinary team of researchers that makes up his lab, which is committed to improving global health, Ismagilov set out to answer those questions. The lab partnered with the Pasadena Public Health Department (PPHD) to launch a large community-based study to investigate how viral load changes in different sample types over time after someone has been infected.

From left: Michael Porter, Alyssa Carter, Jenny Ji, Alex Viloria Winnett, and Reid Akana, who all work in the lab of chemical engineer Rustem F. Ismagilov.

Here's how it worked: contact tracers from local public health departments, clinics, and testing sites, including Caltech's Student Wellness Services, shared study details with people recently infected with SARS-CoV-2 and their uninfected housemates. The 410 participants who enrolled self-collected their samples once or twice a day for about two weeks and sent the samples to the lab to be analyzed with a high-sensitivity research assay. The Ismagilov lab team then calculated viral load in each sample type (saliva, nasal swabs, and throat swabs) to see where the virus accumulated first and figure out how sensitive a diagnostic test would need to be to detect the virus in that sample.

Although they are still analyzing data, Ismagilov's team has released three preprints online and a publication in the *Journal of Clinical Microbiology* that outline several important findings thus far: the virus generally appears first in oral samples, which suggests that many early infections are not being detected by nasal-swab tests; viral load is highly variable among sample types, suggesting that there is no single best COVID-19 test type and better testing strategies are needed; and taking COVID-19 tests first thing in the morning helps improve test sensitivity significantly, suggesting a simple change that can make tests more reliable.

Ismagilov says performing a large study like this amid the pandemic added challenges to every aspect, from getting the study organized, designed, and launched, to running the study and securing the necessary and often scarce lab reagents.

"It would have been easier to do nothing, but the team felt very strongly they had to make this contribution," Ismagilov says.

The Ismagilov lab's COVID-19 study is already having a ripple effect on the group's future work. To make the COVID-19 study a reality, the group built a new infrastructure for conducting longitudinal community-based studies, says Natasha Shelby, scientific research manager for the Ismagilov lab and study administrator for the COVID-19 study.

"That infrastructure will open so many doors to study health conditions that have been challenging to understand," she says, adding that the group has plans to publish their study-design templates to help other labs launch similar studies and get critical data right when a new pathogen emerges.

"We answered the questions we set out to answer," Ismagilov says. "I witnessed incredible dedication and self-sacrifice, not only from our lab but from many other members of the Caltech community, including volunteers who made the study possible."

Yaser Abu-Mostafa is a professor of electrical engineering and computer science. The student research that led to the creation of the CS156 model was supported by Caltech trustee and alumnus Charles Trimble (BS '63, MS '64); the Summer Undergraduate Research Fellowship program; and the Clinard Innovation Fund, established by entrepreneur and Caltech alumnus Gary Clinard (BS '65, MS '66).

Pamela Björkman is the David Baltimore Professor of Biology and Bioengineering and a Merkin Institute Professor. Her work on a universal vaccine is funded by the Merkin Institute for Translational Research, Wellcome Leap Inc., the National Institutes of Health, and the Bill & Melinda Gates Foundation, among other supporters.

Richard Flagan is the Irma and Ross McCollum-William H. Corcoran Professor of Chemical Engineering and Environmental Science and Engineering. His face-mask studies were funded by Caltech's Jacobs Institute for Molecular Engineering for Medicine.

Rustem F. Ismagilov is the Ethel Wilson Bowles and Robert Bowles Professor of Chemistry and Chemical Engineering, a Merkin Institute Professor, and director of the Jacobs Institute for Molecular Engineering for Medicine. His COVID-19 study has been funded in part by the Bill & Melinda Gates Foundation, the Ronald and Maxine Linde Center for New Initiatives at Caltech, and the Jacobs Institute for Molecular Engineering for Medicine.

Read the online version of this story to learn about more of Caltech's COVID-19 research, including a biosensor developed by medical engineer Wei Gao:

The **POWER** *of* Observation

After a decade in space, the small but powerful NuSTAR space telescope still has more to see.

NASA's Nuclear Spectroscopic Telescope Array (NuSTAR), led by Caltech and managed by JPL, turned 10 years old in June. This space telescope detects high-energy X-ray light and studies some of the most energetic objects and processes in the universe. The mission's principal investigator is Fiona Harrison, the Harold A. Rosen Professor of Physics and the Kent and Joyce Kresa Leadership Chair of the Division of Physics, Mathematics and Astronomy at Caltech. Here are some of the ways NuSTAR has opened our eyes over the last decade:

Seeing X-Rays Close to Home

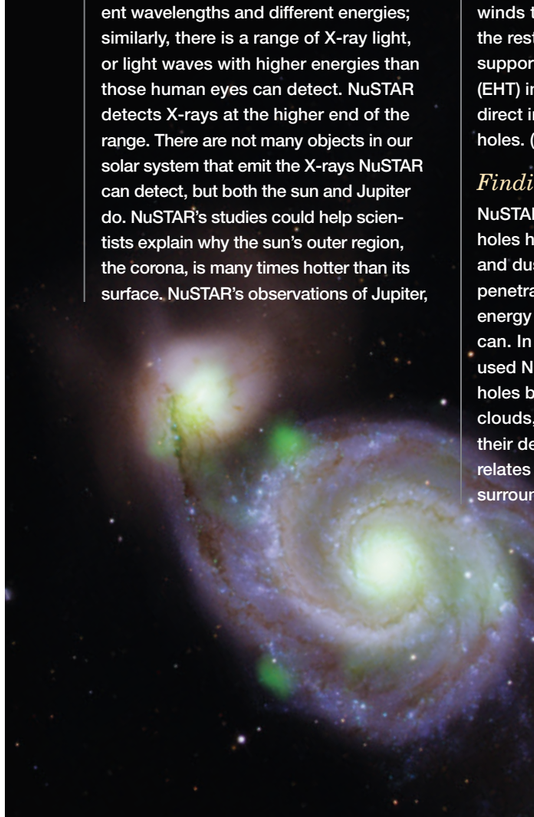
Different colors of visible light have different wavelengths and different energies; similarly, there is a range of X-ray light, or light waves with higher energies than those human eyes can detect. NuSTAR detects X-rays at the higher end of the range. There are not many objects in our solar system that emit the X-rays NuSTAR can detect, but both the sun and Jupiter do. NuSTAR's studies could help scientists explain why the sun's outer region, the corona, is many times hotter than its surface. NuSTAR's observations of Jupiter, made contemporaneously with JPL's Juno mission, found that high energy X-rays are produced as particles slam into the planet's atmosphere.

Illuminating Black Holes

Black holes do not emit light, but some of the biggest ones we know of are surrounded by disks of hot gas that glow in many different wavelengths of light. NuSTAR can show scientists what is happening to the material closest to the black hole and reveal how black holes produce bright flares and jets of hot gas that stretch for thousands of light-years into space. The mission has measured temperature variations in black hole winds that influence star formation in the rest of the galaxy. Recently, NuSTAR supported the Event Horizon Telescope (EHT) in its effort to capture the first-ever direct images of the shadows of black holes. (For more on EHT, see page 20.)

Finding Hidden Black Holes

NuSTAR has identified dozens of black holes hidden behind thick clouds of gas and dust. Visible light typically cannot penetrate those clouds, but the high-energy X-ray light observed by NuSTAR can. In recent years, scientists have used NuSTAR data to find out how black holes become surrounded by such thick clouds, how that process influences their development, and how obscuration relates to a black hole's impact on the surrounding galaxy.



Bright green sources of high-energy X-ray light captured by NuSTAR overlaid on an optical-light image of the Whirlpool galaxy and its companion galaxy, M51b (the bright greenish-white spot above).

Fiona Harrison, NuSTAR principal investigator

Revealing the Power of 'Undead' Stars

NuSTAR is a kind of zombie hunter: It finds the undead corpses of stars. Known as neutron stars, these are dense nuggets of material left over after a massive star runs out of fuel and collapses. Though neutron stars are typically the size of a large city, they are so dense that a teaspoon of one would weigh about a billion tons on Earth. Their density, combined with their powerful magnetic fields, makes these objects extremely energetic: one neutron star located in the galaxy M82 beams with the energy of 10 million suns.

Solving Supernova Mysteries

Stars are mostly spherical, but NuSTAR observations have shown that when they explode as supernovae, they become an asymmetrical mess. The space telescope solved a major mystery in the study of supernovae by mapping the radioactive material left over by two stellar explosions. It traced the shape of the debris and in both cases revealed significant deviations from a spherical shape. Because of NuSTAR's X-ray vision, astronomers now have clues about what happens in an environment that would be almost impossible to probe directly. The NuSTAR observations suggest that the inner regions of a star are extremely turbulent at the time of detonation.

Tiny Lifeforms, Big Impact

By Andrew Moseman

The Center for Environmental Microbial Interactions' support of early-stage projects reaps big rewards for science and scientists.

One late summer morning, Jared Leadbetter returned to his office and found a surprise growing in the sink.

For decades, microbiologists had hunted for microbes whose growth is fueled by oxidizing manganese, an abundant element found across nature and in materials such as steel. Geochemical evidence suggests such microbes should not merely exist but abound across many environments, yet these particular metal eaters had remained frustratingly elusive. Since the search for such microbes had befuddled so many researchers before, continuing to hunt for them seemed futile. Instead, Leadbetter, an environmental microbiologist, filled some idle moments in the lab by searching for microbes that might interact with manganese in entirely different ways.

Fortunately for Leadbetter, he forgot to do the dishes. Upon returning from a 2015 summertime guest-teaching stint at the Marine Biological Laboratory in Woods Hole, Massachusetts, Leadbetter found that he had left dirty glassware containing manganese to soak in the office sink. In the intervening three months, the manganese in the glassware had turned from a light beige to a dark brown, possibly a sign that bacteria had oxidized the manganese. Now all he had to do was prove it.

Former Caltech researcher Hang Yu collaborated with Leadbetter on what would become years of hard work to confirm these really were the long-sought-after microbes. After completing his doctoral studies under Victoria Orphan, a geobiologist and director of Caltech's Center for Environmental Microbial Interactions (CEMI), Yu wanted to further investigate these manganese metabolizing bacteria. CEMI made it possible. "When Hang left my group," Orphan says, "CEMI was able to support him to do a short postdoc with Jared and take this new novel culture Jared had discovered over the finish line." Their initial study on these metal-eating microbes became a paper in the journal *Nature* and a microbiology sensation, one that could, for example, be useful for treating water containing manganese (which often discolors drinking water and has an unpleasant taste).

Formed a decade ago in recognition that researchers across the Institute's divisions study microbial life in some way, CEMI has grown to include more than 10 percent of Caltech's faculty. Thanks to philanthropic funding, the program can support several pilot projects annually and has backed 80 in its 10 years of existence. These projects may have big potential but are often in the early stages of discovery, which means they are not quite ready for the federal grant application process. The researchers doing that work probe questions that will aid in the fight against antibiotic-resistant infections, lead to better ways to clean up the environment, and illuminate the links between the human brain and the microbiome. CEMI is Caltech in microcosm, catalyzing the Institute's signature brand of interdisciplinary collaborations and bold new ideas in the field of microbial interactions.

Orphan says the center's nimble nature allows it to deliver support right when it is needed, such as with Yu's postdoctoral research or to explore new ideas that come from students rather than from principal investigators.

"We do microbiology in a very different way," Orphan says. Caltech researchers inspired by the features and talents of microbes have tried to use their unusual properties to discover new chemistries or catalysts. Others—like Orphan, Leadbetter, and biologist Dianne Newman, who was CEMI's inaugural director—focus on microorganisms themselves and how they drive other geochemical cycles, interact in natural communities, and impact environmental habitability in a way that then impacts the whole planet.

"Within CEMI, microbiology is broadly defined in a way that I think gives the students and postdocs a perspective that is unique to Caltech," Orphan says.

For more about CEMI, go to **microbiology.caltech.edu**

There could be 30,000,000,000 microbes on this page

... and a lot of them are good.

If the global pandemic taught us anything, it is that the world belongs to microorganisms. Some, like the SARS-CoV-2 virus or pathogenic bacteria, are dangerous, even seemingly malevolent. But many more are harmless or even beneficial to humans, including the species that make up a person's microbiome. To understand microorganisms is to better understand our planet ... and ourselves.

"Microbes have been driving the planet for billions of years before we ever got here," says Victoria Orphan, a geobiologist and director of the Center for Environmental Microbial Interactions. "Humans are sort of like the last blink of an eye. We evolved in a microbial soup and world, and so it's not surprising that everything about our own physiology, our ecology, our everything is connected in some way to microorganisms."

Watch a video about the research CEMI director Victoria Orphan (above) does to understand the microorganisms that play critical roles in oceanic methane oxidation:

Forging Links

Like Leadbetter's metal-eating bacteria work, CEMI itself owes something to serendipity. A decade ago, Newman says, then-provost Ed Stolper, now the Judge Shirley Hufstedler Professor of Geology, noticed that faculty investigating microbiological questions had been hired across several of Caltech's divisions. This trend was more fortuitous than it was planned, she says, but Institute leadership seized the opportunity.

"What Ed recognized was a chance to have the whole be more than the sum of the parts," she says, "to bring these people together in a way that allowed for interdisciplinary work and the creation of a community that would enrich the activity of any individual group that was interested in microbes."

Newman, who has been part of CEMI since its inception in 2012, is an exemplar of its ethos. Her lab focuses on the physiologies of bacteria that make it possible for them to survive and thrive in the absence of oxygen. Because of CEMI, Newman's techniques, strategies, and students have crossed over to help other Caltech research projects get further than they could alone.

For example, biologist Alexei Aravin studies how foreign DNA is detected and how, at a molecular level, cells know what to do to respond to this invasion. While studying this process in multicellular organisms such as fruit flies over the past decade, he recognized an analogous process that happens in bacteria. When he wondered which species might make an ideal model to investigate the question, Newman used her deep knowledge of bacteriology to point him toward a useful subject. Then, a student in Aravin's lab snagged one of the first CEMI grants to do this work.

"They wound up making a beautiful discovery of the ancestral version of this very important, fundamental pathway in eukaryotes [organisms whose cells have a nucleus] that appears to maybe have originated in bacteria," Newman says.

Aravin appreciated the chance to work with a microbiologist after making the leap into the field from biology. "Sometimes you need help," he says.

Similarly, Priya Chittur, a graduate student working with chemical engineer Julia Kornfield (BS '83), the Elizabeth W. Gilloon Professor of Chemical Engineering, became interested in biofilms, which are communities of microbes that form on a surface. In particular, she wanted to look for exotic properties in biofilms whose cells are oriented in a specific direction, which can create a gorgeous iridescence. "Their unique optical properties are much like what you see with peacock feathers or butterfly wings," she says.

Chittur and Kornfield sought the expertise of Leadbetter, who suggested searching in Southern California. And, in fact, it was on kelp in the Malibu wetlands where Chittur found samples of the biofilms that became the subject of her CEMI research.

Southern California was likewise an inspiration for graduate student Shivansh Mahajan, who wanted to explore the arsenic contamination that is a concern for the region's groundwater. Mahajan received CEMI funding in 2021 for an ongoing study of the mechanisms bacteria use to pump dangerous arsenic out of a cell, a project that unites the expertise of Newman; Doug Rees, the Roscoe Gilkey Dickinson Professor of Chemistry; and Bil Clemons, the Arthur and Marian Hanisch Memorial Professor of Biochemistry.

In addition to such collaborations, CEMI has also launched careers. Elaine Hsiao (PhD '13), now a faculty member at UCLA, received CEMI support to become a senior research fellow at Caltech between graduation and when she secured a full-time faculty position.

"The pilot fund from CEMI was the first grant I received as I was transitioning into my independent scientist position," she says. "It helped to support a new research project that forms the basis of my lab's current research on how microbes in the gut can affect the brain, and it helped me gain confidence and visibility as I began my professorship role."

Scott Saunders (PhD '20) took his CEMI research in a surprising direction. His doctoral work under Newman studied *Pseudomonas aeruginosa*, an important opportunistic pathogen. An understanding of how it survives in the absence of oxygen, he knew, could lead to new ways to fight infections. In the course of earning his PhD, however, Saunders became fascinated with finding better ways to manipulate bacterial genes.

"Now I'm at a medical center, UT Southwestern," he says. "The important, long-term goal is to extend these approaches into a variety of pathogenic bacteria that are related to *E. coli* and *Pseudomonas*. These are important pathogens that cause antibiotic-resistant infections that kill lots of people every year. It is very important to understand their basic biology and develop tools to help us understand them more quickly and more deeply."

A Microbiology Culture

Integral to CEMI's success, Leadbetter says, is that the center taps into the bedrock strengths that define Caltech, namely its intimate size, tradition of collaboration across disciplines, and boldness to move into new research areas. "These interdisciplinary pilot projects seem to emerge out of nowhere because of the tradition we have at Caltech where faculty and students talk to each other across disciplines," he says. "CEMI is about microbial interactions, but it's also about the interactions among members of our community."

Over the past decade, the center built its own unique culture of collaboration and inspiration. Saunders remembers helping set up food and drink for "MicroMornings," a tradition of serving bagels while someone within the microbiology sphere at Caltech described their research. This grew into what are now called "CEMInars," a lecture series that Saunders credits with making him feel like part of a community and giving him the opportunity to connect with Caltech microbiologists who might have far-flung research interests.

Those informal interactions spark further collaborations. Years ago, one of those talks was given by then-postdoctoral scholar Martin Pilhofer, now a professor at ETH Zurich. In attendance was Newman lab postdoc Nicholas Shikuma, now an associate professor at San Diego State University. Shikuma saw in Pilhofer's cryo-electron microscopy work a direct connection to his own research in bacteriology. Together, they discovered a new class of molecular syringes, which are natural structures released by bacteria. These molecular syringes then interface with an animal and inject a protein into it that triggers its metamorphosis.

"One of the most thrilling scientific moments in my life actually came one afternoon when Grant Jensen [professor of biophysics and biology], Martin Pilhofer, Nick Shikuma, and I were sitting in my office looking in real time at the data they'd collected," Newman says. "The things we started seeing visually just blew our minds. They were structures no one had ever seen before, and this discovery resulted directly from the creativity of these two postdocs and their meeting through CEMI."

The omnipresence of microbes creates an unlimited array of possibilities for CEMI's second decade. In addition to continuing to promote collaborations among the center-affiliated researchers, Orphan also hopes to forge new partnerships with similar centers around campus, including the Resnick Sustainability Institute, the Tianqiao and Chrissy Chen Institute for Neuroscience at Caltech, and the Merkin Institute for Translational Research, due to microbiology's deep and powerful connections to those burgeoning fields of study. Growing CEMI's endowment would also help to build its educational program by offering fellowship support for students and postdoctoral scholars alongside the pilot-project funding the center has supplied for 10 years.

"The main currency of success is really the people," Orphan says. "We have the ability to bring people in and support them and teach them the novel ways we think about microbiology here at Caltech, and then send them off so they can share that with their future universities and careers. If we could expand that bubble out even further, that would be wonderful."

Jared R. Leadbetter is a professor of environmental microbiology. His work is funded by CEMI, the Division of Geological and Planetary Sciences, and the NASA Exobiology program.

Dianne Newman is the Gordon M. Binder/Amgen Professor of Biology and Geobiology and executive officer of Biology and Biological Engineering. Her work is funded by the National Institutes of Health, the National Science Foundation, the Schwartz-Reisman Collaborative Science Program, the Doren Family Foundation, the Simons Foundation, the Jane Coffin Childs Foundation, and the Damon Runyon Cancer Research Foundation.

Victoria Orphan is the James Irvine Professor of Environmental Science and Geobiology and the Allen V. C. Davis and Lenabelle Davis Leadership Chair for CEMI. Her work is funded by the Department of Energy, the National Science Foundation, NASA, the Gordon and Betty Moore Foundation, the Simons Foundation, and the Nomis Foundation.

Nearly 50,000 microbes could sit on the tip of this needle.

In Memoriam

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

Roy W. Gould (1927–2022)

Roy W. Gould (BS '49, PhD '56), Caltech's Simon Ramo Professor of Engineering, Emeritus, passed away on February 19, 2022, at age 94. Gould joined the Caltech faculty as an assistant professor of electrical engineering in 1955, a year before earning his doctorate. His research focused on plasma physics and thermonuclear fusion, and he served from 1970 to 1972 as director of fusion research at the Atomic Energy Commission, the federal agency created in 1946 to manage the development, use, and control of nuclear energy. He was recruited to serve as a deputy science adviser to President Richard Nixon, but returned to Caltech instead. Back on campus, Gould constructed a tokamak, a device that uses a magnetic field to confine plasma and study its chaotic mechanics.

Eugene N. Parker (1927–2022)

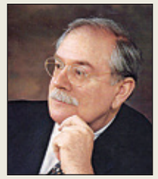
Distinguished Alumnus Eugene Parker (PhD '51) passed away on March 15, 2022, at age 94. Parker was a pioneer in the field of heliophysics, the study of the sun and how it affects Earth, the planets in our solar system, and space beyond. In 1958, Parker correctly predicted the existence of the solar wind, a flow of charged particles that stream off our sun at speeds faster than sound. NASA named its Parker Solar Probe, a mission currently traveling around the sun, in his honor. The mission, which launched in 2018, was the first named by NASA after a living scientist.

Arthur D. Riggs (1939–2022)

Distinguished Alumnus Arthur D. "Art" Riggs (PhD '66), a pioneering geneticist and world-renowned expert in diabetes, died March 23, 2022, at age 82. Holder of the Samuel Rahbar Distinguished Chair in Diabetes & Drug Discovery at City of Hope in Duarte, California, his research profoundly impacted the health and treatment of millions of people with diabetes and cancer, and helped to launch the genetic engineering revolution and the biotechnology industry. In the late 1970s, together with City of Hope's Keiichi Itakura and Herbert Boyer of UC San Francisco, Riggs developed technology that enabled the bacterial production of human insulin. Monoclonal antibody technology developed by Riggs and his colleagues also formed the basis of drugs to treat breast and colon cancer, lymphoma, and autoimmune diseases such as rheumatoid arthritis.

Carl V. Larson (1940–2022)

Distinguished Alumnus Carl V. Larson (BS '52), passed away on March 27, 2022, at age 92. A native of Mercer Island, Washington, Larson enrolled at Caltech in 1948. He initially intended to study chemistry, but he eventually switched to mechanical engineering. Over decades, Larson and his wife, Shirley, engaged actively with the Caltech community—often behind the scenes and anonymously. Larson served as president of the Caltech Associates and chairman of the board for the Summer Undergraduate Research Fellowships program. Larson was also adamant that one should "give good people the resources and get out of the way." He would often remark—using an aerodynamic analogy inspired by his time as a weather forecaster in the U.S. Air Force and his enthusiasm for vexillology (the study of flags)—that his only intention was to "increase lift without adding drag."



David A. Evans (1941–2022)

David A. Evans (PhD '67), a former Caltech faculty member in the Division of Chemistry and Chemical Engineering, died on April 29, 2022, at age 81. Evans studied synthetic organic chemistry at Caltech. After a stint at UCLA, he returned to Caltech as a professor of chemistry in 1974. He stayed with the Institute until 1983, when he joined the faculty of Harvard University. Evans' most influential work involved what is now known as the Evans acyl oxazolidinone method, which is used in the synthesis of polyketides, a class of molecules that are useful as pesticides, pigments, antibiotics, anti-cancer drugs, and medications for treating high cholesterol.

Endnotes

What do you remember most about your Caltech commencement day?

Several of the other electrical engineers had created a new type of audio amplifier. They rented several stadium speakers and set them up on the rooflines of the adjoining buildings. When the band started to play, the engineers poured several kilowatts of "The Ride of the Valkyries" into the courtyard, overwhelming every other sound.

Bruce Casner (BS '75)
NEENAH, WI

My immigrant father was always a man of few words; he was not easily pleased, and he was never one for much pomp and circumstance. But on that June day, I think he felt and appreciated what a special place Caltech is, as did I and the rest of my family. This sense of honor and pride has been a source of much happiness from that day until today.

Demetrios Missios (BS '88)
LONG BEACH, CA

My mother took a picture of the wrong person receiving a diploma!

Robert Murphy (BS '84)
JAMUL, CA

My parents were there. They had doubts about me going for a science PhD after I graduated from college with a BA in English. But when I finally received my PhD in physics, they were so proud. They have passed away since, but I'll always remember that day with them. And the great party we had that evening at my home with so many of my fellow graduates—the relief I felt at achieving my dream was amazing. My parents danced along with my friends.

France Córdova (PhD '79)
SANTA FE, NM

President Rosenbaum's smile at each and every degree recipient. Maintaining such a genuine smile for hours is not possible without a certain inner peace!

Harsha Reddy (MS '18)
PASADENA, CA

We had the first President Bush speak at our commencement. I recall all the extra security. Plus the class president leaning in to ask the president something before giving him a hug. His question? "Can I give you a hug? Or will the Secret Service tackle me?"

Michael Kwan (BS '91)
SUNNYVALE, CA

I was very happy! David Baltimore joked: "MIT got Bill Clinton. We got Bill Nye. Who is jealous of whom?"

Richard Yeh (BS '98)
BROOKLYN, NY

Our commencement speaker, Ray Bradbury, turned to the graduating PhDs and told them: "I want you to go home tonight and call up every person who ever told you that you couldn't do it, and tell them to go to hell." I carried that energy with me all the way through graduate school.

Sarah Milkovich (BS '00)
LOS ANGELES, CA

My mother spotted Richard Feynman on the Olive Walk and tried to line up a photo of me so he'd be in the background. I suggested we go over and ask if he would pose with me. Of course, he obliged, even though I am a biologist! She created a poster of the adorable photo, which my dad hung in his office.

Robin Wilson (BS '86)
BALTIMORE, MD

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

Connect with us

Join the conversation

Email us at **magazine@caltech.edu**

And remember to get social:

Caltech
magazine

1200 East California Blvd., Pasadena, CA 91125

Jad Abumrad, creator and former co-host of the public radio podcast *Radiolab*, was Caltech's 2022 commencement speaker. In his speech, he relayed the story of the monarch butterflies that pass through California on their migration from Canada to Mexico, noting that their journey is so long that it requires three or four generations to complete. "You might not be the first butterfly," he said. "You won't know it, but you might be the third. Or more likely the three hundredth, taking the work or the knowledge or the discovery of those that came before you. And, in your lifetime, you are going to move it forward in ways no one can imagine. And you're not going to get all the way. And that's OK. Because without your effort, humanity is never going to get there."

You can find more 128th Commencement coverage on page 8 and at **magazine.caltech.edu.**