Summer 2019

Caltech
magazine

STRIKING A CHORD

When music and science converge

Also inside:

Biology and big data

Toward greener energy

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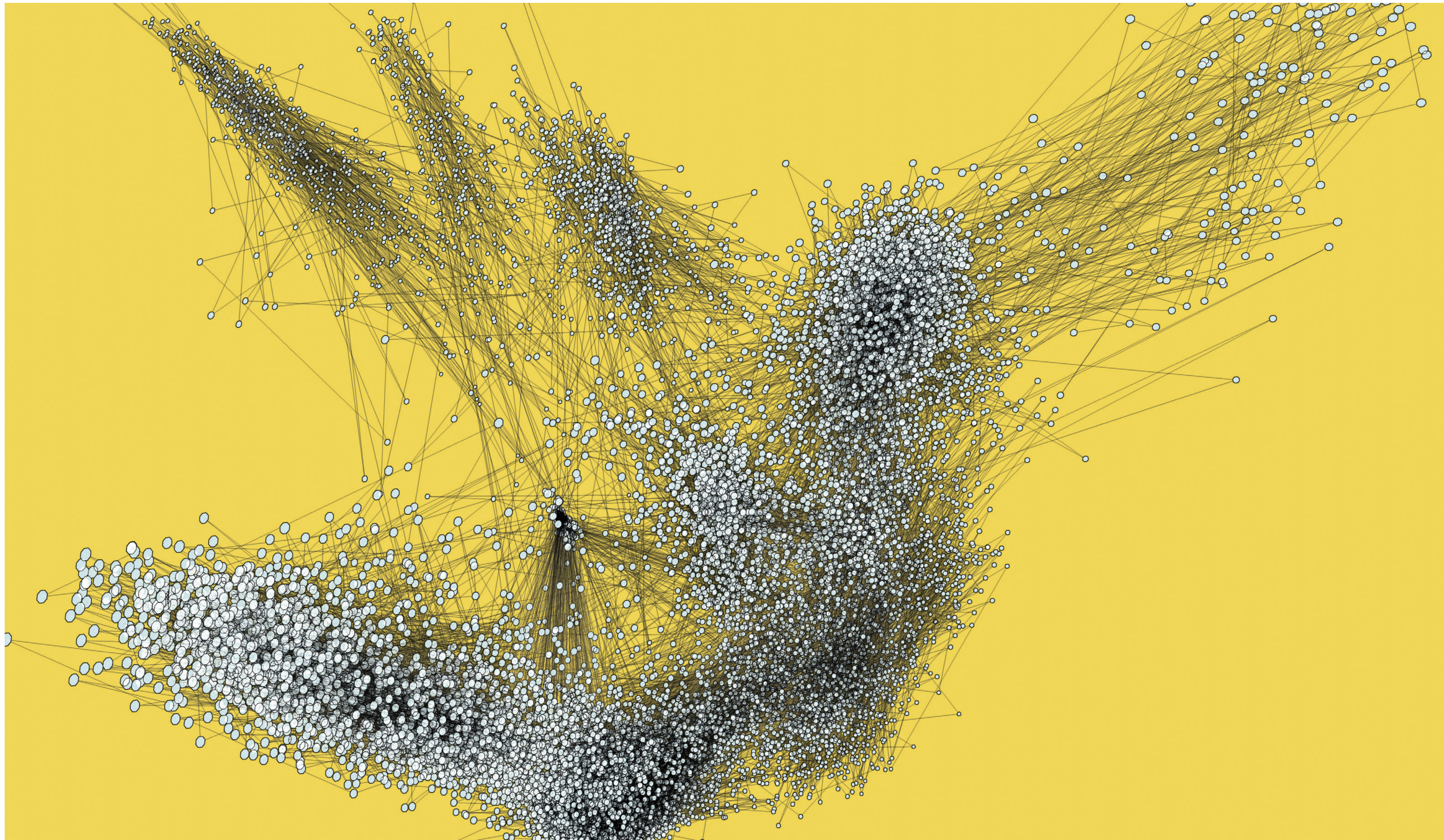

Departments

Cover: Planetary scientist Konstantin Batygin on stage with his rock band Seventh Season.

Left: Santiago Lombeyda, a computational scientist in Caltech's Center for Data Driven Discovery, created this visualization of data points from a large single-cell study.

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Summer 2019 Volume LXXXII, Number 2

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

Printed by Lithographix, Inc., Hawthorne, California.

Image Credits: Michael L. Wong: cover; Santiago Lombeyda/Caltech's Center for Data Driven Discovery: TOC, 24-25; Courtesy of Aaron Ames Lab: 3; Jim Barry: 4; iStock.com/Saddako: 12 (squirrel); Bill Youngblood (Sean Carrol): 12; Courtesy of Kim See: 18-19; Long Cai Lab: 27; Nathanaël Prunet: 28 (bottom); Center for Advanced Methods in Biological Imaging Analysis (CAMBIA) at Caltech. T cell image acquired by Mary Yui: 29 (right); Courtesy of Les Deutsch: 33; Dan McKenna: 34; Gina Chen: 35; William Harrison: 36; Division of Geological and Planetary Sciences: 39; iStock.com/Xurzon: 40 (top); iStock.com/CHBD: 40 (right); iStock.com/Graftner: 40 (middle left); NASA Goddard Space Flight Center Scientific Visualization Studio, https://creativecommons.org/licenses/by/2.0/: 40 (bottom left); Wikimedia/Andrew J. Hanson, Indiana University.

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Game of Thrones inspired this whiteboard artwork seen in the Broad Center. **But who drew it?** If you know, send a note to **magazine@caltech.edu.**

FSC label here

Letters

More *Drosophila* dons

The article on *Drosophila* research ["A Fruitful Collaboration," Spring 2019] fails to take note of my undergraduate biology teacher Professor George Beadle, who won the Nobel Prize in Physiology or Medicine in 1958 together with Tatum and Lederberg, based in part on his earlier work on the development of eye pigment in *Drosophila*.

We undergrads thought that was a big deal! He was also an excellent teacher.

S. Gill Williamson (BS '60)

Turtle tale

I just got around to reading the Summer 2018 edition of *Caltech* magazine (yes, I'm way behind on my reading). It's a wonderful issue and great reading, as usual.

I was particularly impressed with the article on "Fictional Caltech," and how many very well-known novels talk about Caltech.

I was also intrigued by the "Endnotes" section and several rather clever book titles and first lines. I didn't see my entry, but that's no surprise: you must receive hundreds of responses to your requests for alumni input. I don't remember exactly what I wrote, but I certainly quoted the actual title and first line of my actual (children's) book centered around Caltech: *Katy's Astonishing Adventures with Tortulus T. Turtle.*

It made me wonder how many novels have been written by Caltech graduates centered around life at Caltech.

Gerald Ash (MS '65, PhD '69)

Building Keck

The "Building Keck: An Oral History" article [Winter 2019] brought back an old memory of mine.

Back in the mid-1970s, as undergraduates, Ken Severin ('78) and I … were browsing around Robinson and came upon a file cabinet in the hallway. Inside the cabinet were hundreds of large manila cards, each about 14 x 18 inches. On the cards were drawings of a circular item with myriad notes and details handwritten in pencil. They were dated. They were old. It was plain they were construction logs for the Hale Telescope mirror! Right there in a cabinet in the hallway! We could flip through days and weeks of events, following the grinding out of cracks and imperfections. We could almost feel the fear in the handwriting as cracks grew and the relief as they disappeared.

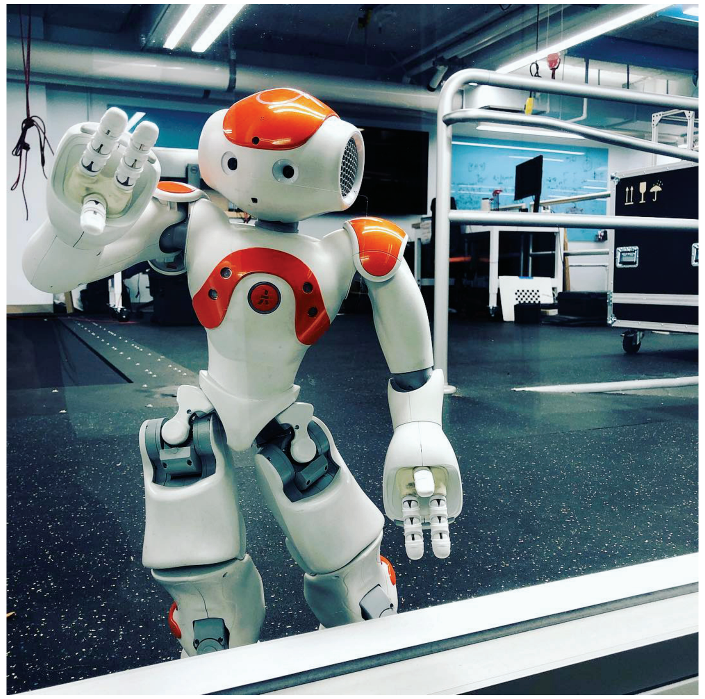
We returned on another night, partly just to relive the excitement. But then there were midterms, then projects, and eventually Commencement. I returned years later when I was a graduate student, but the cabinet was gone. No one in nearby offices had any idea what had happened to it. Many times I wondered whether or not those notes had been discarded and if, perhaps, I was the last to view them and to appreciate the personal touch in those handwritten notes.

Steve Trimberger (BS '77, PhD '83)

The first interest in a large telescope started at the annual meeting, in 1959, of three astronomy departments, Berkeley, UCLA, and Lick Observatory. I was then on the faculty at Berkeley. Otto Struve suggested that the University of California look into building a 200-inch telescope. We agreed that Lick should take the lead.

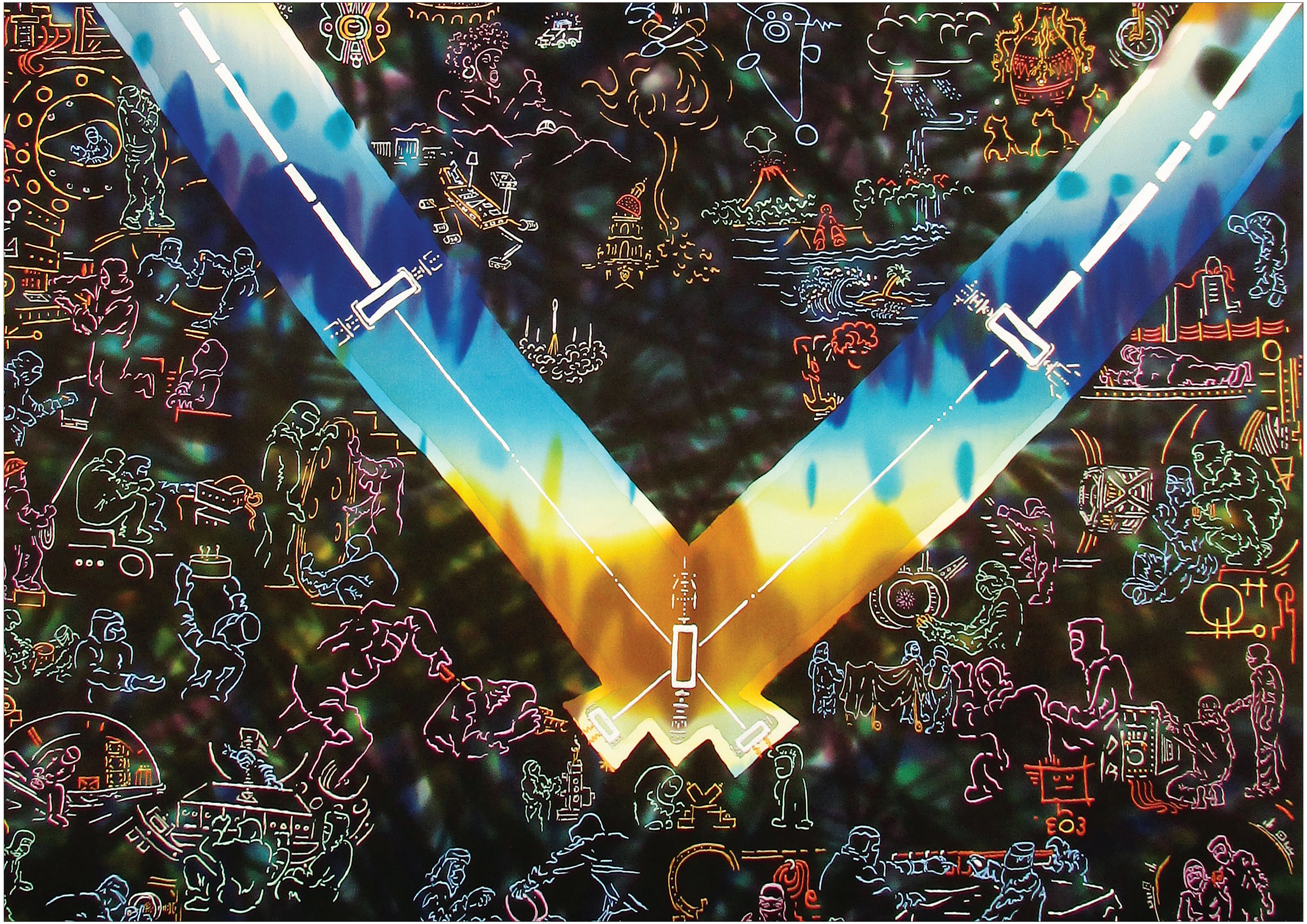
A site survey within the state was initiated by Merle Walker (and in Australia by Bob O'Dell). One peak of about 5,000-feet altitude in the coast range and a 14,000-foot peak east of Bishop looked the best, but the weather in the coastal range was recognized to be rather cloudy, and there were significant access problems due to dirt roads and snow in eastern California. We were aware that many years ago Gerard Kuiper had called attention to the summit of Maunakea as a likely infrared site because of its altitude and location south of the usual Pacific storm track. Leadership of the project was taken up by Robert Kraft, of Lick. He was very effective in getting the campuses together and getting the support of the administration of the University of California.

George Wallerstein (PhD '58)



amber_lab_caltech Nao is waiting to greet our next tour group of future engineers

Caltech's AMBER (Advanced Mechanical Bipedal Experimental Robotics) Lab, led by Aaron Ames, the Bren Professor of Mechanical and Civil Engineering and Control and Dynamical Systems, is devoted to research in bipedal robotics, locomotion, nonlinear and hybrid systems, and prosthetic design.



SoCaltech

- Lending before banks
- Meet Instagram innovator Alex Phillips
- Coding for kids
- A podcast for polymaths

Making Art out of Science

"The nice thing about teaching art here is that I've had the chance to get to know many creative research scientists and engineers," says Jim Barry, Caltech's drawing, painting, and silkscreen art director. "People will invite me to visit their labs and learn more about the science of everything from gravitational waves in space to the geology of rivers."

Barry, who joined Caltech more than 30 years ago, was more recently inspired to base a larger portion of his own art projects on Caltech work. "That's when I went to see some old friends from LIGO [the Laser Interferometer Gravitational-wave Observatory] and got an idea of what was going on there," he recalls. "I created a large silk painting [a portion of the work is shown at left] of the LIGO detectors and all sorts of related scenes, including ancient observatories, noise from earthquakes, and the ghost of a leftover charge from a specialized mirror cleaner."

Next up, says Barry, is a deep dive into the ideas of quantum computing and an exploration into ways of depicting the subatomic world through art.

See the whole painting as well as a legend explaining the various scenes at **magazine.caltech.edu/post/making-art**

"We can abstract away all of the astrophysics of the problem and really just think of it as a purely computational imaging problem. We have these sparse, noisy data, and our challenge is to find the image that actually caused it."

—**Katie Bouman,** *who will join Caltech's faculty as an assistant professor of computing and mathematical sciences in the Division of Engineering and Applied Science in June. Bouman is a member of the Event Horizon Telescope (EHT) team and worked on the computational imaging that recently helped capture the first-ever image of a black hole.*

Four Questions for:

Jean-Laurent Rosenthal and Philip T. Hoffman

In their new book, *Dark Matter Credit: The Development of Peer-to-Peer Lending and Banking in France,* Caltech's Jean-Laurent Rosenthal (at right, in photo) and Philip T. Hoffman (at left), along with their co-author Gilles Postel-Vinay, a professor emeritus at the Paris School of Economics, make the case that money borrowing and lending thrived in 18th- and 19th-century France without the help of banks. By sifting through archival data on 250,000 French loans, the researchers were able to uncover a shadow system of peer-to-peer lending. The system let nearly a third of French families borrow money in 1740; by 1840, it funded as much mortgage debt relative to gross domestic product as U.S. banks did in the 1950s.

1. What is the main message people should take away from your book?

JLR: Credit markets in Europe were really big before banks became important players in financial markets.

PTH: And the findings were a surprise because all this lending was going on without anything like our modern credit scores or even a way to tell if property had been mortgaged. It shows how ingenious people can be under the right conditions.

2. Do the lessons from this book have any practical applications for today's credit markets?

JLR: At first blush, this book is about a system of peer-to-peer lending that goes back centuries but didn't disappear until just before World War II. In that way, it is really history. But history is full of useful lessons, and the most important one for credit markets is that they will only thrive when reliable information can flow from borrowers to lenders. Building banks when the information system is deficient will lead to little lending or worse yet, financial crises.

PTH: The book's lessons apply to modern peer-to-peer-lending, which is cropping up around the world thanks to the Internet. In China, it has attracted over 50 million investors, but because the firms arranging the loans misled investors, the whole market collapsed in 2018. A bit of government regulation would have helped, as in other financial markets.

3. What were your favorite and least favorite parts of researching and writing this book?

JLR: The best part was working with Phil and Gilles. When we disagreed, everyone sat down and articulated how data would discriminate between our different arguments. And then we would go and collect what was needed, which was just educational and fun. My least favorite part was putting together a final database from data collected beginning in the 1990s. It took me a long time to be sure I had the best version of the data for each of the 160 localities we included.

PTH: Each of us brings something different to our research, and that is why it is a real delight to work together and figure out how to tease the data we need out of the surviving historical records. My least favorite part was going through the manuscript to check that the numbers in every table, graph, and sentence matched that final database.

4. Do you have any other books planned?

JLR: I have started to work on a book about wealth inequality in Paris from 1807 to the present.

PTH: I have a book underway on why the Industrial Revolution happened first in Europe and not somewhere else, such as China. And the three of us have another book project in mind as well about a huge financial collapse in 1740s Paris that cost powerful people a fortune. It's a great story, worthy of a movie!

Jean-Laurent Rosenthal is the Rea A. and Lela G. Axline Professor of Business Economics and the Ronald and Maxine Linde Leadership Chair, Division of the Humanities and Social Sciences. Philip T. Hoffman is the Rea A. and Lela G. Axline Professor of Business Economics and History.

Read the full interview at **magazine.caltech.edu/post/rosenthal-hoffman**

UNDERGROUND OPERATION

For DARPA's latest Grand Challenge robotic competition, the SubT Challenge, teams of autonomous robots are tasked with rapidly mapping, navigating, and searching underground environments under the supervision of a single remote operator. CoSTAR, the JPL/Caltech team, led by JPL's Ali-akbar Agha-mohammadi and Caltech's Joel Burdick, has passed the qualifying rounds. This summer, CoSTAR will compete in the tunnel section of the competition at a yet-to-be-disclosed location.

August 2018 When CoSTAR found out it had won a slot in the contest

5 Number of DARPA challenges Joel Burdick has worked on

3 Number of years over which the SubT Challenge will take place

7 Number of teams selected for funding by DARPA

$1.5 million a year for 3 years Amount DARPA is funding selected teams

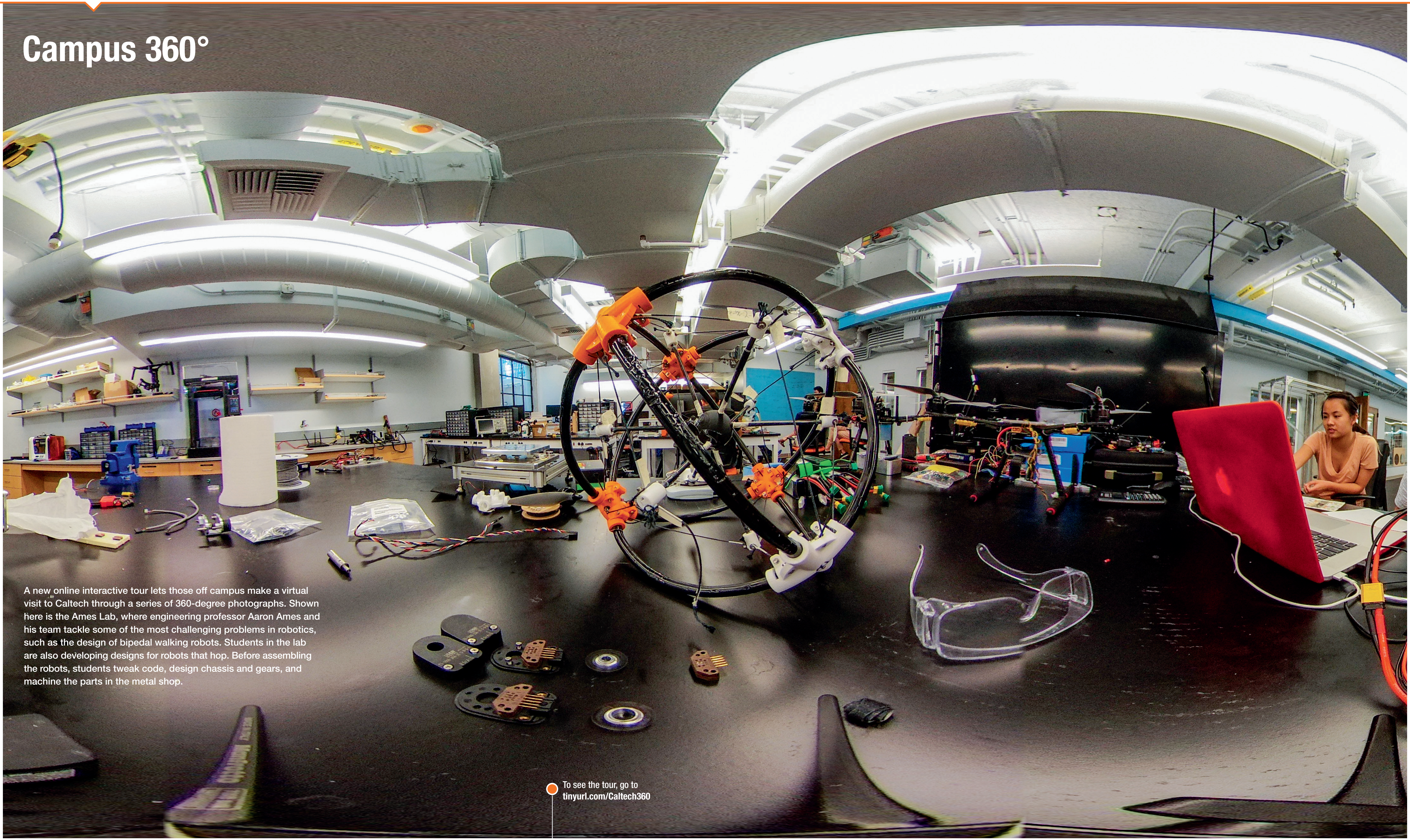
≈ 8 kilometers Length of the underground course DARPA will build

3 Number of environments robots will need to master (tunnels, urban underground, and natural caverns)

? Number of robotic vehicles the team will need to build. (Too soon to tell.)

>40 Number of CoSTAR team members

Campus 360°



A new online interactive tour lets those off campus make a virtual visit to Caltech through a series of 360-degree photographs. Shown here is the Ames Lab, where engineering professor Aaron Ames and his team tackle some of the most challenging problems in robotics, such as the design of bipedal walking robots. Students in the lab are also developing designs for robots that hop. Before assembling the robots, students tweak code, design chassis and gears, and machine the parts in the metal shop.

To see the tour, go to tinyurl.com/Caltech360

Alex Phillips (fourth-year graduate student)

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

Alex Phillips, a fourth-year geochemistry student, is the founder and curator of the @women.doing.science Instagram account.

"Science is a lot more than women in white lab coats holding up beakers. On social media, I see a lot of headshots of scientists, but I just don't relate to headshots! Do scientists get dressed up in a suit each day and smile? That's not what science is. Science is being in the lab running a column, being out in the field collecting rocks, going on a boat, working on your computer doing models, and I think that kind of representation is missing from social media. When I looked for an Instagram account posting action photos of women doing all sorts of things in science, there wasn't a single one. So, I thought maybe I should just make one. ... so I did! When I started last June, I thought if I reach 1,000 followers, I would be proud! Now we have over 40,000, which is kind of amazing. And the cutest thing is that my dad still 'likes' every single picture. He's our biggest fan."

For more #SoCaltech, go to tinyurl.com/MagSoCaltech

Class Act: Coding for Kids

On Friday afternoons, Caltech computer science students visit public schools in Pasadena to help third-, fourth-, and fifth-graders learn to code. Their work is part of a recently introduced course in which Caltech undergrads study and practice strategies for teaching programming to children.

"We start with basic concepts, and by the end, students have coded their own games in Scratch [a visual programming language developed for children]," says senior Anna Resnick, who helps lead the class as a teaching assistant. "A few have even told us they want to be programmers someday."

Stepping up

The coding initiative started about five years ago when a Pasadena Unified School District teacher requested Caltech's help with computer science instruction, says Mitch Aiken, the Institute's associate director for educational outreach. Around the same time, a group of first-year students at Caltech expressed interest in teaching coding.

A pilot program, in which student volunteers visited schools to deliver programming lessons, proved promising, Aiken recalls. But organizers determined that more students would be able to consistently commit time to the project if it were part of a formal class rather than a volunteer effort.

"It reminds our students why they were first inspired by computer science," says Claire Ralph, lecturer and outreach director for Caltech's computing and mathematical sciences department. "And it's an opportunity to give back, another way to have an impact on the field."

Easy access

For participants, undergrads, and elementary schoolers alike, the experience can also make computer science seem a little more accessible, Ralph says.

"For our students, it's a good reminder of how far they've come," she says. "It can be easy to underestimate how much you've learned and how much you know. You have to really understand something well to be able to explain it to a fifth-grader."

"I've always loved teaching, helping people understand things," senior Steven Brotz says. "The kids are all familiar with computer games. We have the chance to help them understand how those games get created."

Looking ahead

Alix Espino, a Caltech senior, hopes the time she spends with younger students encourages them to consider careers in computer science.

"I felt like it was important for me to get involved because there are not a lot of Latinos in tech, and this school [Jefferson Elementary] is predominantly Latino," Espino said. "I thought I could be a good role model."

Caltech senior Anna Resnick shares basic coding skills with Natalia Jimenez at Pasadena's Jefferson Elementary School.

"Most students are willing to work very hard and dedicate substantial time and energy to learning if they know that what they are doing is worthwhile. That is why it is so important for them to know why a certain seemingly obscure mathematical concept or a physical phenomenon matters and where it fits in the grand scheme of things."

—Ali Hajimiri

Winner of Caltech's 2019 Feynman Prize for Excellence in Teaching and Bren Professor of Electrical Engineering and Medical Engineering in the Division of Engineering and Applied Science

Back on Campus

Astrophysicist and Caltech alumna France Córdova (PhD '79) stepped onto the Beckman Mall stage on June 14 as the speaker for Caltech's 125th commencement ceremony.

Since former President Obama appointed her director of the National Science Foundation in 2014, Córdova has developed initiatives that cut across fields of scientific discovery, technological innovation, and STEM education.

Formerly president of Purdue University, Córdova also served as NASA's chief scientist in the 1990s. At the time, she was the youngest person and the first woman to hold that position.

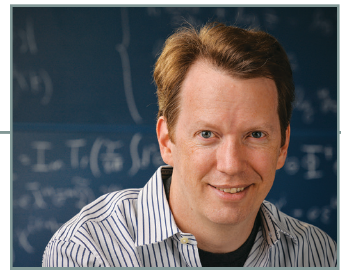
Prefrosh Visit? Solved!

The almost 300 students who visited Caltech in April for the Institute's Prefrosh Experience, a welcome event for newly admitted first-year students, were greeted by two oversized Rubik's cubes balanced on the lawn of the admissions office. Attendees at the three-day event formely known as Prefrosh Weekend got to stay overnight in student residences, meet current students, and interact with members of the Caltech community.

Squirrel added for scale

Extracurricular:

Sean Carroll Versus the "Science Silo"



While science is a powerful tool for understanding our universe, it is not the only one, insists Caltech theoretical physicist Sean Carroll. On *Mindscape,* his new podcast, Carroll hosts conversations with interesting thinkers on topics across the spectrum: from superstring theory to the fall of Rome.

Carroll first became interested in podcasting after guest appearances on podcasts hosted by others. To come up with the format, he drew on his experience interviewing diverse thinkers for his latest book, *The Big Picture.* "Really, a podcast is just my excuse to talk to a bunch of interesting people," he says.

Those "interesting people" have included scientists such as Caltech's Mike Brown and Kip Thorne, of course, but also historians, musicians, movie critics, conservationists, theologians, and activists. Featuring guests beyond the field of science is central to the premise of *Mindscape.* "There's a certain way in which people who do economics, or law, or philosophy, or anything else can spread out their thoughts a little more widely," he says. Carroll also hopes to tear down barriers. "I want to establish that science should be a part of this interconnected ecosystem," he explains, "rather than off in a separate silo."

New episodes of Mindscape are posted weekly and can be found on Carroll's website at ***preposterousuniverse.com/podcast.***

In the Community

STEMonstrators Connect with Local Students

Graduate student Stephanie Threatt (second from the right) shows Blair High School students an experiment involving liquid nitrogen during a recent STEMonstration.

When Sarah Sam, a graduate student in neurobiology, realized that some of Caltech's Pasadena neighbors knew nothing about the Institute, she decided to do something about it.

"I've been really close to campus and found people who didn't know what Caltech was," explains Sam, who is also president of the graduate-student-run group Black Scientists and Engineers of Caltech (BSEC), "and that was really surprising to me because we're this world-renowned prestigious institution, and for people in Pasadena, right outside the university, it's not even on their radar."

In the spring of 2018, Sam and several of her fellow BSEC members launched STEMonstrations, an outreach project that now also involves Caltech's Club Latino. STEMonstrations brings STEM to students in the Pasadena Unified School District (PUSD), a minority-majority district, through scientific demonstrations led by Black and Latino Caltech graduate students.

Building a relationship between Caltech and its local community was central to BSEC's vision for the outreach program from the start, as was a focus on diversity. "We were looking to get Caltech in touch with a lot of the underrepresented public school students who are locally around us who didn't otherwise have connections to the university," explains BSEC member Kyle Virgil. "The drive was to show students who are of an age when they are thinking about their opportunities in life and what's available to them, what it looks like to be a person of color doing high-level science, while simultaneously sharing cool science experiments."

Since launching their project, the STEMonstrators have visited a new classroom every term. During each one-hour session, students are guided through three science demos covering areas related to Caltech research topics such as neurobiology and solar energy. But the project is not only about bringing kids fun science experiences. As graduate student and STEMonstrator Stephanie Threatt explains, "the people who you're exposed to, who teach you, you see as really at the forefront of a given field. That influences you being able to see yourself in that field. So seeing yourself in role models and in people who hold positions in STEM is really important."

Making connections with young people with an interest in science has been one of the most rewarding experiences for the STEMonstrators, who spend time speaking with the students in the school cafeteria after the demonstrations. "If we just went, did the experiments, and then left, just showed up and said 'hey, this is science,' it wouldn't be the same. It would miss the whole point of the demonstration," says Virgil.

The STEMonstrations project is part of a wider landscape of Caltech outreach initiatives. "It's awesome that so many people on campus volunteer their time to do science demonstrations, like science nights," says Sam. "But I think there was that diversity element missing. Our program is coming from scientists who look like the students we're trying to engage."

—Elise Cutts

Meet the STEMonstrators at **magazine.caltech.edu/post/stemonstrators**

Origins

Fountain of Knowledge

Sitting in the shade of fruit trees in the Beckman Institute courtyard, you can watch small birds drink from the fountain that trickles quietly there. The fountain's basin is a Moorish-inspired four-leaf-clover design, but above that it takes a very Caltech turn.

A polyhedron of 38 triangular and square granite faces, the fountain borrows its shape from the Archimedean solid known as a snub cube. Water flows from its top and tightly hugs the geometric form, giving the cube a shimmery quality.

The Beckman Institute was built in 1989 as a collaborative space for biologists and chemists. The Institute's founding director, Harry Gray, was charged with designing a fountain for the building's central courtyard that would represent the aims of the building and its inhabitants.

Gray and crystallographer Bill Schaefer settled on the snub cube design because of its likeness to ferritin, a protein composed of a core of thousands of iron atoms surrounded by an organic protein shell. With its inorganic and organic components, the protein seemed a perfect representation of the Beckman Institute's goal of combining chemistry and biology.

Once they had their concept, Gray and Schaefer set out to secure funding for its construction. To persuade Caltech's then-president Marvin Goldberger that the multifaceted shape would function well as a fountain, the pair constructed a model of the cube from cardboard and carried it, along with a pitcher of water, into Goldberger's office.

Accounts diverge on whether Gray actually poured water over the cube or merely teetered the jug over the president's expensive rug, but Gray distinctly remembers Goldberger saying, "Stop, Harry, I'll give you the money."

—Lori Dajose

Toward a Greener Energy Landscape

How Caltech chemist Kimberly See is energizing battery research.

by Emily Velasco

Shrinking glaciers and a shriveling snowpack, dying forests and dwindling water supplies. These are just some of the challenges faced by the state of Colorado as global temperatures continue to rise. Colorado is, of course, not alone in facing these challenges. But for Caltech chemist Kimberly See, that's where it hits home. She grew up in the state, and it was there that she developed an appreciation for the natural world and an acute awareness of the harmful effects humans can have on it.

Both that appreciation and awareness drive See's research at Caltech, where her lab is pursuing the future of batteries, work she sees as critical for easing humanity off its dependence on fossil fuel.

See's story begins a little outside Golden, Colorado, a former mining town turned Denver suburb. Golden sits where the Rocky Mountains' towering peaks begin to blend with the plains and prairies that grow ever flatter as they stretch out to the Mississippi River. A pair of craggy mesas overlook the city's downtown, and a creek tumbling out of the foothills bisects it. It was a place with an abundance of opportunities for an adventurous and curious child to explore the outdoors and ponder how it all works.

"I was always hiking and playing outside when I was a kid," See says. "I started getting really interested in science as a way to understand what was going on in the world around me. I wanted to know things like, 'How does this plant use sunlight to grow?' and what I ended up realizing was that chemistry was a really great way to find out."

Her interests in chemistry and nature grew in stepwise fashion, punctuated by pivotal moments: first, the day a high school teacher gathered her class to watch as she threw a chunk of sodium metal into a pond to demonstrate an explosion, and second, watching a water-splitting reaction while an intern at the National Renewable Energy Laboratory in Golden.

"That's when I started doing photoelectrochemical water splitting, and that's when I started to really like electrochemistry," she says. "I also saw what we're doing to the environment, and I found that was a cause worth fighting for. Diversifying our energy landscape and reducing our impact on climate change is directly related to my love for nature."

In grad school at UC Santa Barbara, See was presented with an opportunity to study batteries, and she took it, seeing it as an extension of her previous studies in electrochemistry and a way to have an effect on climate change.

"It was this great combination of studying concepts from a perspective of electrochemistry and solid-state chemistry, with applications in electric vehicles, grid storage, and all of these things that would help with the CO_2 emission problem," she says.

Now an assistant professor of chemistry at Caltech, See has established her own lab and continues her work on batteries. Her research is focused not on making incremental improvements to the same batteries we already use but rather on inventing new batteries with new uses.

Solid Effort

The first attempts to build solid-state batteries began in the late 1950s. These attempts did not succeed because the materials of the day were not sufficient.

"What we're doing is kind of jumping 10 steps ahead and saying, 'OK, well, why don't we try to develop an electrolyte that allows us to conduct magnesium or zinc?'"

"We work under the assumption that lithium-ion batteries are reaching their theoretical limitations. To provide the change that's needed for widespread electric vehicles or inexpensive grid storage, we need a new mechanism to store energy," See says.

That new mechanism could come in the form of batteries that ditch the liquid electrolyte present in essentially every modern battery currently in use and replace it with a solid electrolyte. These solid electrolytes would come with a few advantages: they would never leak, unlike the batteries left in a remote control for too long; they're not flammable, unlike the liquids used in lithium batteries; and they could allow for the use of dense metal anodes, so batteries could pack more energy into a smaller volume.

See's lab hopes to combine solid-state electrolytes with elements other than the ever-popular lithium. Currently, the team is looking at zinc and magnesium as contenders.

"What we're doing," she says, "is kind of jumping 10 steps ahead and saying, 'OK, well, why don't we try to develop an electrolyte that allows us to conduct magnesium or zinc?'"

It is not a trivial proposition. Liquids are exceedingly good at conducting ions, but solids not so much. That is because a liquid's molecules are mobile, and that mobility makes it easy for ions to travel through them. In a solid, the molecules are much more rigidly fixed in place, which makes it difficult for ions to squeeze past them.

So, the challenge for See's lab is to design a solid that lets the ions slip through on their way from the battery's anode to its cathode. Recently, the research team announced their first success in doing so. The material they designed is a solid, but it contains a molecular structure that is somewhat flexible. That flexibility allows its bonds to bend out of the way as zinc ions pass through. Previously developed materials of this sort needed to be brought to high temperatures to work, but the team's new material works at near room temperature.

Graduate student Sarah Bevilacqua says that innovative approach to batteries is just one of several things that drew her to See's lab.

Energy density is the amount of energy a material can pack into a volume. Modern lithium-ion batteries are still 100 times less energy dense than gasoline.

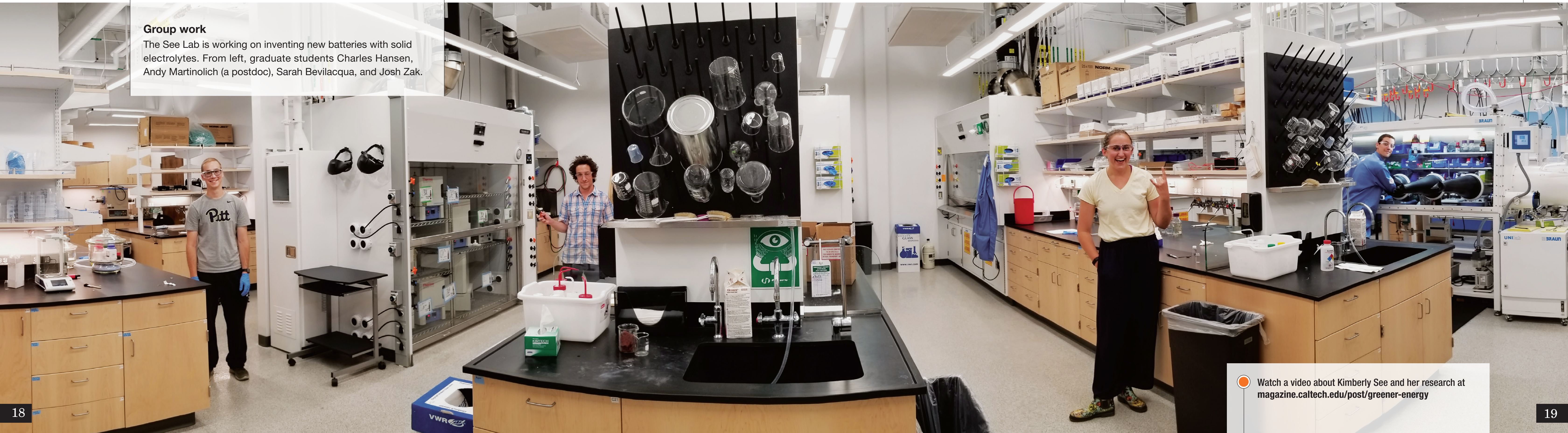
"She's the most genuinely enthusiastic-about-science person I've ever met," Bevilacqua says. "And she really wants us to succeed. Whenever I've got frustrations, or I'm not making progress, she makes time for me."

But the best thing about working in See's lab, Bevilacqua says, is helping to take science into completely new territories.

"We're really trying to implement new chemistry," Bevilacqua says. "There's a huge chemical space to play around in, so the possibilities are pretty exciting, as opposed to taking a lithium-ion battery and making it just 1 percent better. The world is our oyster when it comes to new batteries."

See, for her part, is excited as well. She says she has found Caltech's environment stimulating, and that has inspired collaborations with Marco Bernardi, assistant professor of applied physics and materials science; Kathy Faber, Simon Ramo Professor of Materials Science; Theo Agapie (PhD '07), professor of chemistry; and Scott Cushing, assistant professor of chemistry.

"The support here at Caltech has been amazing. They really give you the tools you need to do the science you want to do, which has been such a privilege," she says. "To build a lab that's geared toward the science you want to do is a really, really amazing experience."

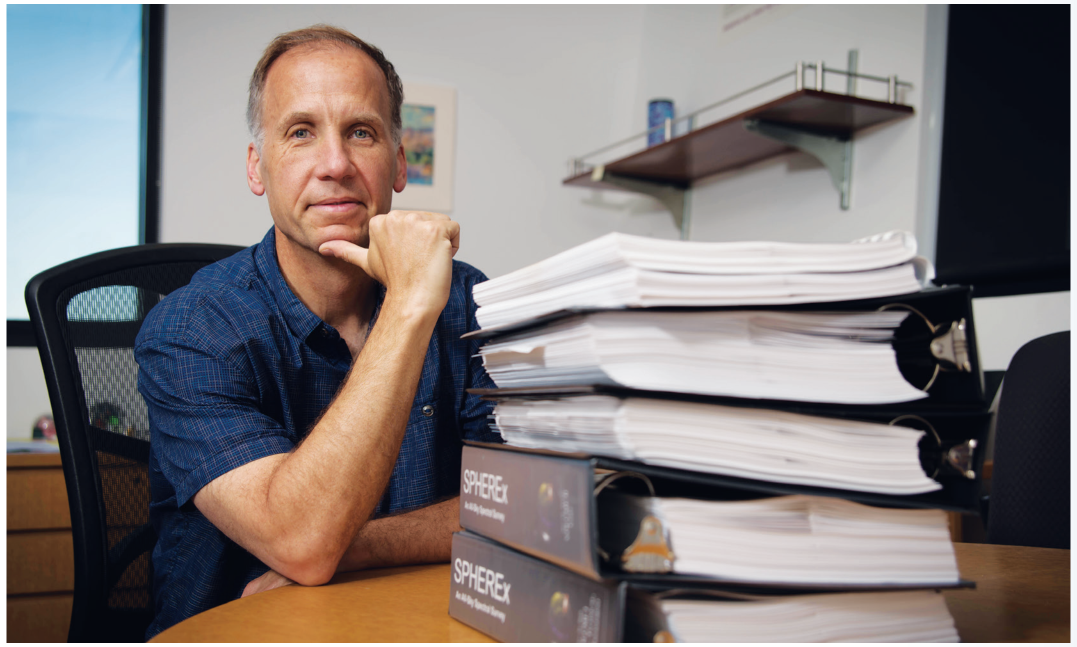


Group work
The See Lab is working on inventing new batteries with solid electrolytes. From left, graduate students Charles Hansen, Andy Martinolich (a postdoc), Sarah Bevilacqua, and Josh Zak.

Watch a video about Kimberly See and her research at magazine.caltech.edu/post/greener-energy

Pictured below: Jamie Bock with the 2,700-page space mission proposal.

On a MISSION



by Whitney Clavin

In February, Caltech's Jamie Bock received some good news: NASA had selected the space-mission proposal he had been working on laboriously for more than six years.

"I was elated to hear the news," says Bock, a Caltech professor of physics and senior research scientist at JPL, which is managed by Caltech for NASA. "My team and I are thrilled to finally move from writing proposals to the design and building stage."

When it begins science operations in 2023, the mission, called SPHEREx (for Spectro-Photometer for the History of the Universe, Epoch of Reionization and Ices Explorer), will be the first to take near-infrared spectra everywhere over the entire sky. Its goal is to answer questions about the birth of our universe, the role of water and organic ices in the formation of planetary systems, and the cosmic history of galaxy formation.

Caltech magazine sat down with Bock to ask about the proposal process as well as the next steps for the mission.

What gave you the idea to propose this mission?

There were actually three different mission concepts being discussed back in 2012. I was involved with one idea to study the inflationary birth of the universe; another group wanted to study interstellar ices; and a third was looking at galaxy evolution. We decided to join forces and create and propose one mission, SPHEREx. These diverse science themes come together by taking spectra over the full sky, or what astronomers refer to as the celestial sphere, hence the name of the mission.

Can you tell us more about how the proposal process works?

NASA will put out an "Announcement of Opportunity" (AO) targeting either astrophysics or heliophysics science. When the AO comes out for a mission, you have 90 days until the proposal is due. That's way too late to come up with new ideas; really you need to be winding up the proposal writing at that stage. Thanks to NASA, we generally know when the AOs are coming, and SPHEREx got off to an early start.

During the first proposal round, the review panel looks at all aspects of the mission but emphasizes science potential. From typically a dozen proposals, NASA then selects three mission concepts for further study.

What was the most stressful part of the process?

Crunch time comes when finishing the reports. That always comes down to the wire. We would meet every day and on weekends in the "war room." It would be filled with snacks, and we covered the walls with pages of the proposal. I quickly learned that it's impossible for a single person to oversee all the sections going into the proposal: you succeed or fail based on your team.

One of the most stressful aspects of this process are the site visits, when the panel of about 30 reviewers come to JPL for the day and fire questions at us. You have to say things clearly in the fewest words possible. But I confess I did not enjoy the practice reviews with a "mock" review board. Their job is to give us a worst-case site visit experience; they are good at their jobs. We did four all-day practices for this visit, the last one being a dress rehearsal in a suit and tie.

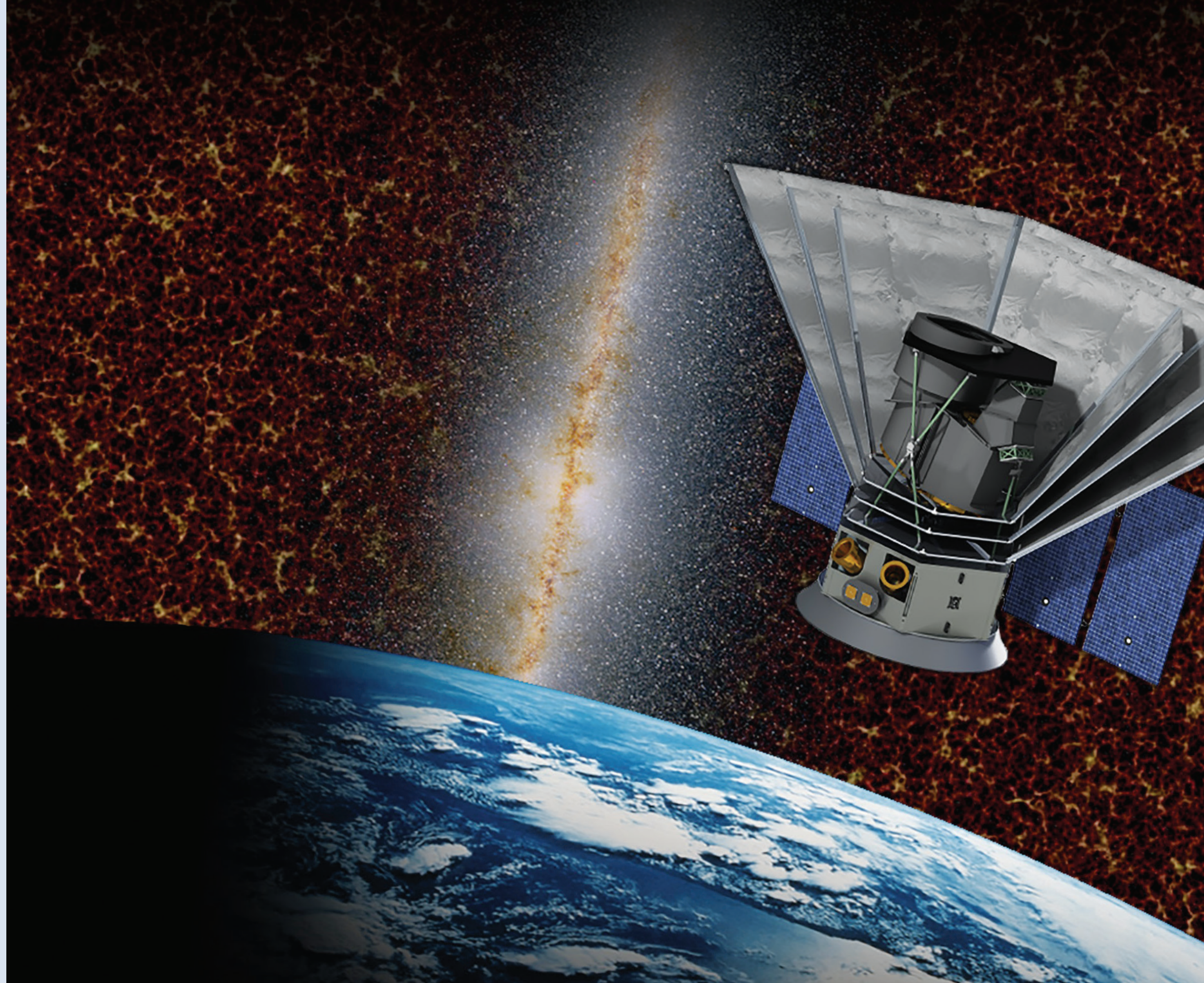
As the principal investigator (PI) of the mission, what is your primary role?

The job of the PI is to ensure that the instrument performs scientifically, that we meet our science requirements.

What are the next steps?

We are just getting started and have lots to do. We have to finish filling out our team We also have to make preparations for the pipeline being developed at IPAC [Caltech's astronomy data and science center], which will automate the data analysis, since it will come pouring in once we are in orbit. The volume of the data is so great that you can't even look at the entire set with human eyes and keep up. Ball Aerospace will build the spacecraft, which is the main body of the space mission. JPL and Caltech will work closely together in building the payload, which is the telescope, detectors, and cooling system that sits above the spacecraft. Together, the spacecraft and its payload will be launched into space on a rocket, but we will have to wait for NASA to select the launch site and procure the vehicle.

At Caltech, we will start designing and building the telescope, detector, and readout system, which will be tested in the basement labs at the Cahill building. We're excited to get busy and roll up our sleeves.



Major partners of the SPHEREx mission include Caltech, JPL, NASA, and IPAC; Ball Aerospace provides the spacecraft; and the Korea Astronomy and Space Science Institute will provide support for instrument calibration and testing. Scientists from across the U.S. and in South Korea will participate in the science analysis of SPHEREx data.

FREELOADING FOR 100 MILLION YEARS

THIS ANCIENT BEETLE INFILTRATED THE EARLIEST-KNOWN ANT COLONIES. ITS MODERN RELATIVES DO THE SAME.

by Lori Dajose

Watch a video of Joe Parker talking about his research at magazine.caltech.edu/post/freeloading-beetles

Almost 100 million years ago, a tiny and misfortunate beetle died after wandering into a sticky glob of resin leaking from a tree in a region near present-day Southeast Asia. Fossilized in amber, this insect eventually made its way to the desk of entomologist Joe Parker, assistant professor of biology and biological engineering at Caltech. Parker (holding the beetle in the photo at left) and his colleagues have now determined that the perfectly preserved beetle fossil is the oldest-known example of an animal in a behaviorally symbiotic relationship.

Symbiotic relationships between two species have arisen repeatedly during animal evolution. These relationships range from mutually beneficial associations, like humans and their pet dogs, to the parasitic, like tapeworms and their hosts.

Some of the most complex examples of behavioral symbiosis occur between ants and other types of small insects called myrmecophiles, meaning "ant lovers." Thanks to ants' ability to form complex social colonies, they are able to repel predators and amass food resources, making ant nests a highly desirable habitat. Myrmecophiles display elaborate social behaviors and chemical adaptations to deceive ants and live among them, reaping the benefits of a safe environment and plentiful food.

Ants' social behaviors first appear in the fossil record 99 million years ago, during the Cretaceous period of the Mesozoic era, and are believed to have evolved not long before, in the Early Cretaceous. Now, the discovery of a Cretaceous myrmecophile fossil implies that the freeloading insects were already taking advantage of ants' earliest societies. The finding means that myrmecophiles have been a constant presence among ant colonies from their earliest origins and that this socially parasitic lifestyle can persist over vast expanses of evolutionary time.

"This beetle-ant relationship is the most ancient behavioral symbiosis now known in the animal kingdom," says Parker, an affiliated faculty member with the Tianqiao and Chrissy Chen Institute for Neuroscience at Caltech. "This fossil shows us that symbiosis can be a very successful long-term survival strategy for animal lineages."

The fossilized beetle, named *Promyrmister kistneri*, belongs to a subfamily of "clown" beetles (Haeteriinae), all modern species of which are myrmecophiles. These modern beetles are so specialized for life among ants that they will die without their ant hosts and have evolved extreme adaptations for infiltrating colonies. The beetles are physically well protected by a thick tank-like body and robust appendages, and they can mimic their host ants' nest pheromones, allowing them to disguise themselves in the colony. They also secrete compounds that are thought to be pacifying or attractive to ants, helping the beetles gain the acceptance of their aggressive hosts. The fossilized *Promyrmister* is a similarly sturdy insect, with thick legs, a shielded head, and glandular orifices that the researchers theorize exuded chemicals to appease its primitive ant hosts.

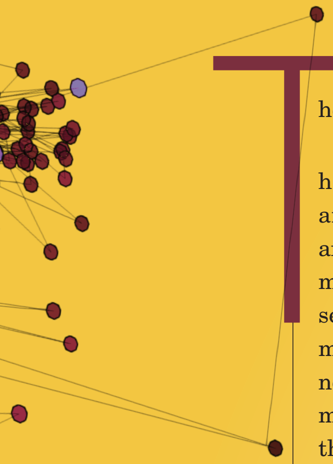
Depending on another species so heavily for survival has its risks; indeed, an extinction of the host species would be catastrophic for the symbiont. The similarities between the fossilized beetle and its modern relatives suggest that the particular adaptations of myrmecophile clown beetles first evolved inside colonies of early "stem group" ants, which are long extinct. Due to *Promyrmister's* remarkable similarity to modern clown beetles, Parker and his collaborators infer that the beetles must have "host switched" to colonies of modern ants to avoid undergoing extinction themselves. This adaptability of symbiotic organisms to move between partner species during evolution may be essential for the long-term stability of these intricate interspecies relationships. [C]

Funding for this research was provided by the Rita Allen Foundation, the Shurl and Kay Curci Foundation, the Esther A. & Joseph Klingenstein Fund, Inc., and the National Natural Science Foundation (China).

Biology & big data

How computational biology is shaping the future of health and privacy.

by Lori Dajose



The study of living things is undergoing a revolution.

In the past few decades, cutting-edge biological tools have enabled the rapid collection of unprecedented amounts of data. Biologists and bioengineers have amassed countless terabytes of high-resolution videos of microscopic cells as they wiggle and grow and interact; sequenced millions of genomes, from *Escherichia coli* to mice to humans; and tweaked bacterial DNA to reengineer life. Within these vast data sets lie answers to fundamental questions of biology: What are the molecular rules that control development? How are stem cells "wired?" How many different types of cells make up the human brain? Can failures of single cells cause disease?

But manual analysis of all this information is virtually impossible. Fortunately, the fields of computer science and artificial intelligence are undergoing their own rapid development. These tools as applied to the biological sciences have given rise to the field of computational biology.

Lior Pachter (BS '94), **Matt Thomson**, and **David Van Valen** (PhD '11) all recently joined Caltech's faculty as part of an Institute initiative to focus attention on computational biology. *Caltech* magazine sat down with them to discuss the ongoing biological data explosion and its harmonious relationship with computational tools as well as how these intersecting revolutions will change the future of privacy, ethics, and what it means to be human.

What does it mean to study biology? What are the goals and challenges?

Matt Thomson: Doing biology is not only about measuring and observing. It's about actually changing and perturbing the biological systems, making predictions and models, tweaking them based on your observations and doing it all over again.

To give an analogy, let's say you throw a ball up in the air. If you know parameters like the ball's mass, the acceleration due to gravity, its initial velocity, and so on, you can accurately predict where the ball will land after a certain amount of time. We want to predict how biological systems will evolve, but it's difficult because there are so many parameters.

David Van Valen: The first set of parameters you think of are genes. For example, a simple *Escherichia coli* bacterium has 3,000 to 4,000 genes. What does each gene do? How do they interact? Imagine understanding an airplane and all of its component pieces ... an organism is at least 10 times harder.

Lior Pachter: In the past, some may have imagined that it was simple, that one gene encodes for, say, hair color, and another makes you happy or sad. It appears that biology doesn't work like that. It's a very complicated interwoven network of objects that interact in very complicated ways.

MT: Right. Living things are dynamic and heterogeneous, changing and evolving through time and space. Various genes can be expressed at different levels throughout an organism's lifetime.

DVV: You might think that you could just sort of take averages and glean insights that way, but you can't. You can't take a lung and blend it up and sequence all that matter and then understand a lung, because there are different types of cells (epithelial cells, endothelial cells, and so on) in different locations working with one another. We need techniques that can respect these heterogeneous differences in order to understand whole organisms.

But biology is really exciting right now, because for the first time, we're having solutions come up for all of these challenges. Simultaneously.

Can you talk about some of the new technologies that are impacting biology?

MT: In just the past decade, exciting and powerful technologies are emerging, like CRISPR-Cas9, the technique that allows us to edit genomes. The first full human genome was sequenced in 2003, after 13 years of work. Now, in 2019, sequencing all 20,000 genes in the entire human genome takes only a day or two, if not less.

LP: Matt and I work on developing techniques to identify all of the RNA molecules in individual cells within a sample of tissue. Knowing which RNA are present in a given cell can tell you which genes are activated and, therefore, what the cell is trying to do. The basic way RNA sequencing works is to flow cells, one by one, through a narrow pipeline and encapsulate each cell in its own water droplet. Within the droplet, the cell is broken open and all of the messenger RNA molecules inside are tagged with a barcode unique to that particular droplet. Then we gather up all of the messenger RNA from all of the cells and sequence it in one big batch. The barcoding enables us to know which genes came from which cells.

MT: We can profile 100,000 cells in a day and a whole mouse embryo in less than a week. Our colleague Long Cai is aiming to be able to profile 1 million cells in a day.

DVV: Genomic assays give us a sense of the composition of living systems in a way that we can respect their large "parts list." For understanding how things vary in space and time, we have imaging technologies. Our microscopes are now so good that we can look at whole tissues, we can look at single cells, we can look at single molecules. These technologies are starting to talk to one another, too. We basically repurpose machine-learning algorithms to identify individual cells, so that lets us look at things in a way that respects the important differences in datasets that have mixed information. These tools really are going to empower researchers to carry out a new generation of experiments.

From left: Matt Thomson, David Van Valen, and Lior Pachter.

In the 1960s, Gordon Moore (PhD '54) predicted that computational power would double every two years, which has turned out to be quite accurate. Is there a kind of Moore's law-like prediction for biology?

MT: Oh, it's actually super-Moore's law. It's faster.

LP: We've seen that in basically any given biological technology. I don't think there has been, in history, technological progression at this speed ever. Not even in computers.

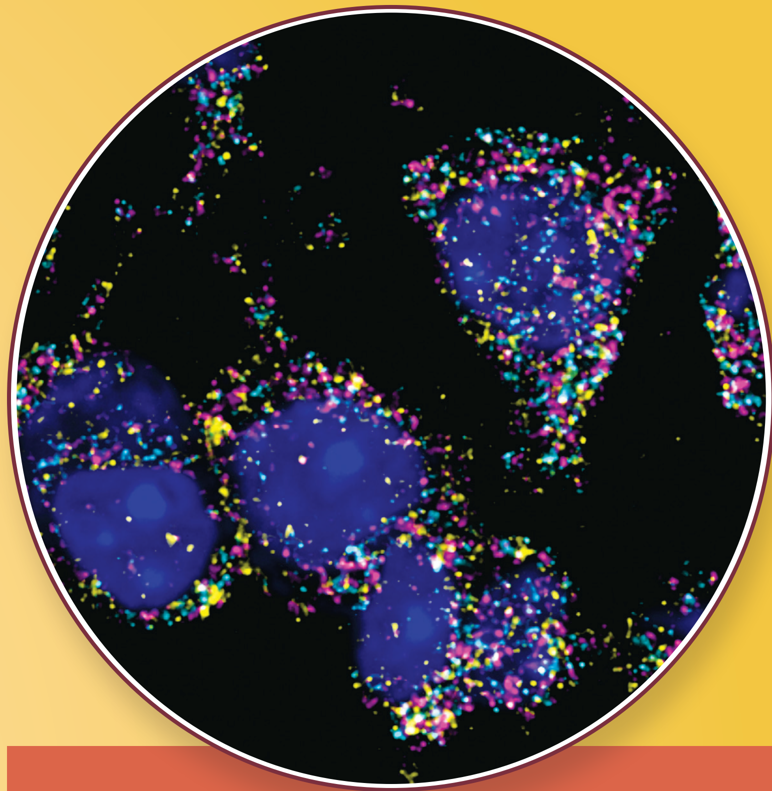
MT: Three years ago, a particular experiment to perturb a biological system and measure responses would require a massive national consortium of scientists, like 200 people, to collect and analyze data over years. Now, our lab can do these sorts of things in a week or so. We need automated and efficient ways to analyze all this data, and that's where machine learning comes in.

What exactly *is* machine learning?

LP: Machine learning is the process of using computational tools to predict and learn from data. These tools can be used in a variety of ways, from combing through telescope data to find planets outside our solar system to teaching a computer how to recognize moving objects in order to drive a car.

DVV: You can give a computer some example data sets and teach it how to look for insights. Then, once it has "learned," you can give it a totally new data set to analyze. It's a kind of artificial intelligence, and it has broad applications.

LP: Some of it even got its start here at Caltech, when



To understand complex biological systems, it is important to know how cells interact with and influence their neighbors. For example, a healthy cell located directly next to a cancerous cell will receive different chemical signals and behave differently than a cell elsewhere in the body. A newly developed technique from the laboratory of **Long Cai** colorfully illuminates every mRNA in every cell within a tissue sample with "super-resolution." The technique can be applied to study everything from embryos to cancers.

Santiago Lombeyda, a computational scientist with Caltech's Center for Data Driven Discovery, created the illustration featured in this article. In this visualization of data points from a large single-cell study, each dot represents a single cell, which consists of 20,000 independent gene expression measurements, that were then mathematically mapped into a 3-D space. Caltech senior research scientist Sisi Chen provided the data and analysis.

researchers in the 1980s were inspired by neuroscience to develop computational methods for data analysis called neural networks.

MT: Many of us biologists are now working with Caltech's AI4science Initiative, which brings together computer scientists and other researchers to use computing tools to get insights from our data. Machine-learning algorithms can be used for problems ranging from detecting fake news to classifying genetic sequences.

What kinds of things can we discover by applying machine-learning tools to biological data sets?

DVV: Image analysis is a big area where machine learning can help. In my lab, we work on repurposing machine-learning algorithms, like the ones used to do computer vision for self-driving cars or that Facebook uses to recognize and locate people in pictures. We refashion them to analyze imaging data from microscopes and make these tools available so that biologists everywhere can use them. For example, a pathologist can use these techniques to look at breast cancer cells and learn about the interactions between immune cells and cancer cells.

MT: We use machine learning to look at really high-dimensional data sets, including genomes and single-cell sequencing data. It can reveal relationships between networks of genes, such as which genes are controlling the expression of other genes in a network. This way we can find the "master genes" that control processes like brain development or that control the development of T cells in the immune system.

LP: The possibilities for what we can learn from all of this biological data are both exciting and sobering. I think we're really not that far from the unimaginable: changing who we are by changing our biology. What does it mean to be you? There are very profound fundamental changes and possible biomedical technology changes that are going to blow us away. It's going to come very fast.

DVV: Society is not prepared for it.

LP: Society is completely unprepared for it!

DVV: These technological developments will drastically reshape what the world looks like, but many of the people who are going to be affected by these tools are not aware of what's happening. There are questions about the medical industrial complex and healthcare system: Should we do basic genetic manipulations on embryos to get rid of disease-causing mutations? How about manipulations to determine eye color, height, skin color? We have to be having deep conversations, as a society, about what we actually want. How do we use these tools to create a just society?

LP: There is a law in the United States that prevents healthcare discrimination on the basis of genetics. But what about other kinds of discrimination? Can a university ask for a prospective student's genome and take genetics into consideration?

So, not only are computer science and biology meeting but philosophy and ethics are becoming part of the conversation as well.

LP: Yes. Here's one example. Private companies are offering to sequence anybody's genome because we have the ability to do that now. But the companies can collect this data, and we need to be having a conversation about the extent to which the data should or should not be private. Who can have access to it? It's complicated and subtle: if somebody makes their own data public, then they are implicitly releasing information about their relatives without their consent.

The genome is actually the most trivial thing that you can measure on a person these days. What if you could take a sample of someone's tissue and figure out aspects of their current state of health and well-being? This would be revolutionary in fighting diseases but also makes it very easy to get deeply personal information about a person.

MT: In parallel, there are all the internet companies that are figuring out your preferences and ideologies based on your search history, your social media friends, the things you post. Tons of data about your personality. Just imagine combining that with genetic data about you as a person. … You could get a full picture of society. Just imagine how advertisers could use this information. Right now, a vast majority of this information is in the hands of private companies.

DVV: Well, this got dark.

LP: On a more positive note, these hypothetical scenarios that we are imagining, the reason we're bringing this up is because we are all aware of how crazily exciting the development is in our field. It's just moving so fast. These are not conversations that are framed in some science fiction world, they're very real. There is so much data and information that has been collected already, and there is a lot to learn from it. I think we are very privileged to come to Caltech and do this now.

DVV: It's one of the unique things that makes Caltech so exciting. We get students who are fascinated by the biological questions but also have the quantitative backgrounds that are now necessary for doing this type of work. C

Lior Pachter (BS '94) is a Bren Professor of Computational Biology and Computing and Mathematical Sciences, as well as an affiliated faculty member of the Tianqiao and Chrissy Chen Institute for Neuroscience at Caltech.

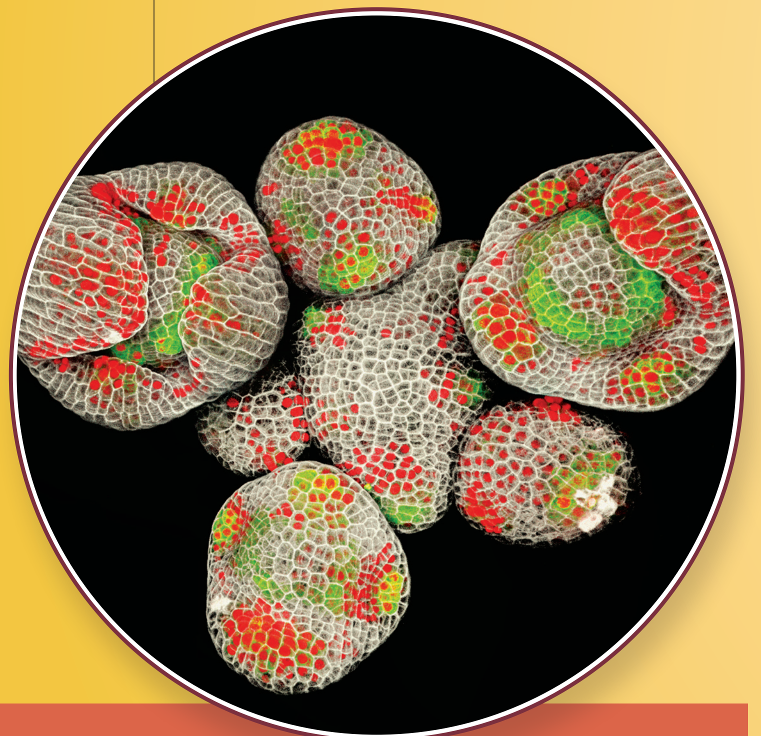
Matt Thomson is an assistant professor of computational biology and Heritage Medical Research Institute Investigator.

David Van Valen (PhD '11) is an assistant professor of biology and biological engineering.

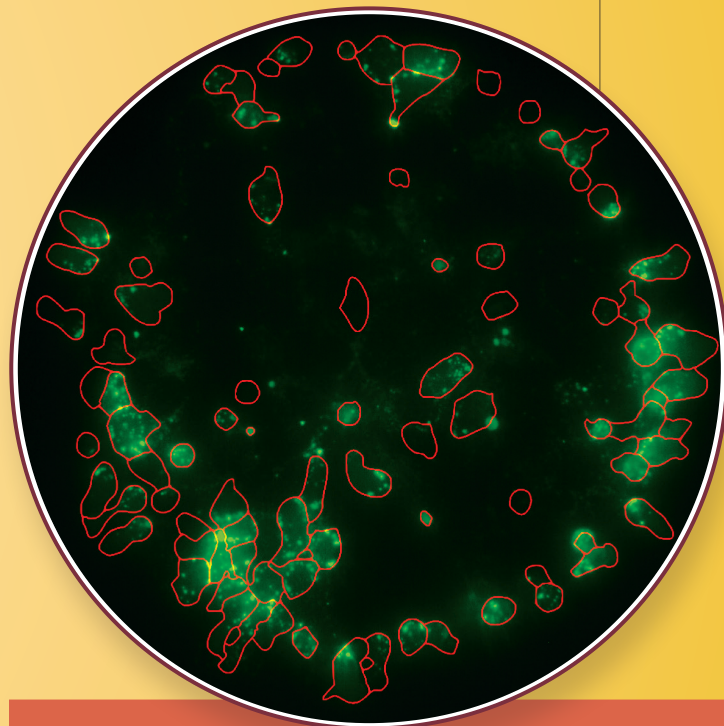
Long Cai is a professor of biology and biological engineering, as well as an affiliated faculty member of the Tianqiao and Chrissy Chen Institute for Neuroscience at Caltech.

Elliot Meyerowitz is the George W. Beadle Professor of Biology and a Howard Hughes Medical Institute Investigator.

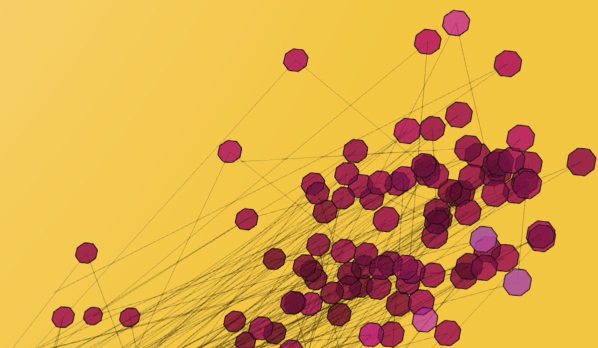
Ellen Rothenberg is the Albert Billings Ruddock Professor of Biology.



How do plants grow? How do plant cells decide to be part of a flower or a stem? What genes do they express? In the laboratory of **Elliot Meyerowitz,** these questions are answered using machine-learning image- analysis tools to learn from detailed images and videos of plant growth and gene expression.



How do certain immune cells, called T cells, develop? How do they interact? What genes do they express, and when? Machine-learning image analysis enables researchers in the laboratory of **Ellen Rothenberg** to analyze T cell development and gene expression in real time.



STRIKING A CHORD

by Judy Hill

When music and science converge

"If I were not a physicist, I would probably be a musician," said Albert Einstein, who nicknamed his violin Lina and was famously ardent about Mozart and Bach. "I often think in music," he added. "I live my daydreams in music. I see my life in terms of music."

The Nobelist was hardly alone among his fellow scientists. Music and science, it seems, have gone hand in hand through the ages: physicist Richard Feynman was an avid bongo player; Russian chemist Alexander Borodin composed Romantic-period music; and Queen's guitarist, Brian May, is a respected astrophysicist. Here at Caltech, a sizable number of scientists also wield a bow, pluck a string, or tickle the ivories. Two in particular have forged powerful links between their research and their musicianship.

For planetary scientist Konstantin Batygin (MS '10, PhD '12), the parallels between music and science are clear. "If you look at a scientific idea, it's just a riff," he says. "It's a melody, but it's not attached to anything. The way that a scientific idea grows into a hypothesis, into a theory, requires all of this additional work where you take an idea, you build it, and you see how it fits in. It's the same with music."

Batygin has been in the spotlight in recent years for his work with Caltech colleague Mike Brown that hypothesized the existence of an as-yet-undiscovered ninth planet ("Planet Nine") in the solar system. That work is deeply exciting to Batygin, but recently he has been just as excited about classical music.

Batygin's forte, he will quickly point out, is not classical music. With his band Seventh Season, he plays hard rock, a genre he has passionately espoused since around the age of 11. Nevertheless, earlier this spring he traveled to Florida to play guitar on a piece of music written by Miami Symphony Orchestra conductor Eduardo Marturet and inspired by Planet Nine.

Konstantin Batygin and Lucy Jones share notes in Beckman Auditorium.

Batygin met Marturet when both were selected for the Genius: 100 Visions project, which collected the insights and visions of top minds around the world in celebration of the 100th anniversary of Einstein's general theory of relativity in 2015. A mutual acquaintance mentioned the ninth-planet hypothesis to Marturet, and the conductor seized on the idea of writing a Planet Nine symphony as an extension to Gustav Holst's Planets suite.

Batygin was not completely surprised that Marturet felt compelled to write a new symphony after learning about a hypothetical ninth planet. "I think there is, among classical musicians, a thing about the planets and the Planets suite," he says. "The other intriguing thing about Planet Nine is that it has this remarkable property where people can resonate with it. It's something that astounded me when we first wrote the original paper. It didn't just get media attention; it seemed to me that people were truly captivated. I think it's at the right intersection of mysterious and tangible. It combines those two curiosities of the human condition in such a nice way, the notion that there's something there in the solar system, in our home solar system, that has yet to be discovered. I think because of that, there's a real magnetism to the Planet Nine hypothesis. That's why you can go out and make art out of it."

To get ready for Miami, Batygin practiced like never before, since, he says. "It turns out being pretty good at rock 'n' roll isn't the same as playing in the symphony."

Music has always been part of Batygin's life. His father, Yuri, also a scientist, had a band, so Batygin grew up watching him play guitar, though, as he notes, "it wasn't really proper to play rock music in the Soviet Union." When the family moved from Moscow to Tokyo, he attended a Japanese elementary school and, as he recalls, basically pretended to play the keyboard amid a "bunch of third graders who were actual virtuosos, just perfect, on every instrument."

He started to learn guitar as a preteen, because, he explains, "that's the time when your brain starts to have weird hormones, and you need to express yourself through A minor, primarily." That was also when he discovered Metallica and became fascinated with heavy metal, both for its technical challenges and the way it pushed the art form to the next level. For a while, he says, he had no other interests than to start the next Metallica.

On the off chance that plan A did not work out, and with a natural affinity for physics, he enrolled at UC Santa Cruz. "I ended up absolutely falling in love with what I do now," he says. He attributes that to his undergraduate adviser, Greg Loughlin, who also, as it happened, played in a band. "I ended up doing cool research and published a paper with Greg in my final year of undergrad," Batygin says. Graduate school at Caltech (he received his PhD in planetary science, working with Dave Stevenson and Mike Brown) followed, and he never looked back. He also kept playing.

"Music isn't just a way to relax, it's a way to keep the imagination part of your brain going in ways that are very correlated with science," says Batygin. "Of course, they're distinct, but the process through which you come up with an idea and then let it take hold and develop in your mind is exactly the same. I take the same approach to writing scientific papers as I do to writing music."

Seventh Season plays locally at Pasadena's Old Towne Pub. "The spirit of rock 'n' roll is very much alive in the Old Towne. The symphony is never going to perform in the Old Towne, but I had this remarkable opportunity to bridge the divide. Who would ever have thought that being a professor at Caltech would lead me to playing in the symphony?"

Les Deutsch

(BS '76, MS '77, PhD '80)
Deputy Director, Interplanetary Network, JPL

Instruments played/owned: Organ, trumpet, saxophone, clarinet, piccolo, flute, drums, violin, banjo, piano, French horn, euphonium

Caltech connections: I've played just about every instrument in the Caltech-Occidental Wind Orchestra. I've played most of the instruments also in the Jazz Band. Starting in 1974, I've been the Caltech organist playing at every commencement.

I've also done a lot of composing for Caltech over the years. For our 100th anniversary, I composed a Centennial Suite, which is a four-movement suite for band that was performed at Bandorama. In 2017, I did a 20-minute piece for Concert Band in honor of the 40th anniversary of Voyager.

Outside of Caltech: I also play in a professional Dixieland band called the Night Blooming Jazzmen. I wish I'd thought of that name.

Musical background: I started organ lessons when I was 11. My father was a chief scientist at North American Aviation at the time and they were looking for something to apply their electronics toward in the commercial market. He proposed they work on a digital electronic organ, something that didn't exist then. In around 1970, the product was released by Allen Organ Company.

Solos vs. teamwork: As an organist, typically you play alone and you don't get that experience of playing with a group, so playing in the bands is important to me. The same is true in doing research. There are things that you do by yourself, and there are things that you do as part of a team. The two fields are very analogous.

As one of the world's most influential seismologists, Lucy Jones is a familiar face to residents of the Southland. But while her post-quake TV appearances have been seen around the world, she is less well known as a dedicated player of the viola da gamba, a stringed instrument similar to the cello.

> "As we go through the really accelerated times of rising temperatures ... I tried to make it sound really frantic."

Recently, Jones, who was a seismologist with the United States Geological Survey (USGS) for 33 years and is now a visiting associate at Caltech, combined her scientific knowledge with her musical affinity, creating a piece of music based on climate-science data. She then performed the work with three fellow gamba players at L.A.'s Natural History Museum on February 1, 2019.

Jones credits her musicianship to her Welsh family. Growing up, she says, "my grandparents would come over for dinner, and instead of saying grace, we'd sing it. In parts. A cappella. It was just part of our family life." Jones took up the cello in fourth grade and discovered chamber music in high school, beginning a lifelong love of small-group ensembles.

As an undergraduate at Brown, studying physics and Chinese, she stumbled across a Renaissance-music group and took along her recorder to audition. Once the adviser discovered she was a cello player, he offered to pay for her to take classes on the viola da gamba. "My joke was that once I discovered the 17th century I never wanted to return to the 20th. It's music I love, and the gamba gave me a chance to do small-group work."

While at the USGS, she played on and off with Caltech's chamber music program: less when her children were small, more once they were grown. She began attending Viola da Gamba Society of America meetings and joined the Los Angeles Baroque, a community baroque orchestra that performs several times a year.

In 2013, Jones started working on her own composition, inspired by a YouTube video in which a cellist demonstrated how much Earth's temperature had been rising by scaling it into pitch. "It was cool," she says, "but it was just chromatic; it wasn't music, just random notes." She was interested in creating something more musical. Her first efforts ended up in the trash can, but the idea lingered, and when she retired from the USGS in 2016 she picked it up again, dividing her time between composing and writing her most recent book, *The Big Ones: How Natural Disasters Have Shaped Us*.

Jones had studied a 17th-century musical genre called In Nomine, in which one instrument plays a simple theme, or base song (from the Latin phrase *cantus firmus*), and other instruments play more complex lines in counterpoint. She used that form for her composition on climate change, taking the temperature data and turning it into the base song.

"It's a little long," says Jones of the final composition, "because it's 138 years' worth of data, since 1880, one measure per year." Back when she first composed the piece, she had scaled it over three octaves, a wide dynamic range. "You're in the lower octave for the first 60 years, and then you're in the next octave for the next 50 years, and then it hits the top of the third octave in 1998. Then it bounces around for a while below that. Nineteen ninety-eight was just one of those freak hot years."

When she came back to the piece and had the opportunity to update it with new data, she realized it had gone up another fifth. "In 2016, it's off the end of the fingerboard," she notes. "Luckily it's a harmonic, so you can play it just by resting your finger on it. It makes it really dramatic how much it's changed at the end."

As a scientist who studies data about our planet, Jones says that when she looks at the figures on climate change she is "terrified" by what she sees and "appalled" at the lack of response. "We aren't scared enough," she insists. One of her goals, then, was to convey feelings about the data in musical form. "As we go through the really accelerated times of rising temperatures, I started using multiple motifs and intentionally having them step on each other. I tried to make it sound really frantic."

She also rewrote the music so it dies away toward the finale. "I sort of strip out the chords and end up on a single note at the end for the uncertain future."

Inspired by her foray into composition and buoyed by the response (the Viola da Gamba Society of America has already published the sheet music), Jones is currently working with a movie composer/filmmaker to build a compelling narrative for a performance that will blend science and music to explore the implications of climate change and what we can do to change that trajectory. [C]

Paul Asimow

(MS '93; PhD '97)
Eleanor and John R. McMillan Professor of Geology and Geochemistry

Instruments: Piano, flute, tuba, conducting

Caltech groups: Wind orchestra

His Caltech musical debut: I auditioned for the concert band on flute, and because I knew how to conduct [then band director] Bill Bing gave me the wonderful privilege of being permanent guest conductor and doing one piece of my own choosing every semester.

On working with Glenn Price as band director: He's taken a good group and made it outstanding, with more ambitious programming, larger-scale works, and higher expectations. Now I definitely have to show up for rehearsal every week prepared and on my best game, because he can tell if you're not!

Why it's worth his time: I'm eternally grateful to be here at Caltech because the musical groups are open to people other than students. As a tuba player, if I weren't here, I certainly would have given it up years ago because I wouldn't have had an opportunity to perform.

How playing the tuba and conducting are not so different: The tuba is the bass line. It's not necessarily what people are listening to when they're listening to a group. But to me, playing the bass line well and conducting a group have a lot in common. You have to be aware of the ensemble so you're playing at the right volume, and you're also leading the group and giving them cues in rhythm and in pitch.

Julia Greer

Professor of Materials Science, Mechanics and Medical Engineering

Instrument: Piano

Caltech group: A trio with cellist Monica Kohler and violinist Tony Kukavica (Class of '21).

Why music is still part of her life: I've been playing since I was 5 or 6. I grew up in Moscow. Every little Russian girl has to take piano lessons. I just never quit. As amateurs, we have the best of both worlds. Because we've built the tool set to get to the technical level that allows us to actually produce the kind of sound that we want to hear, it's enjoyable. When you don't quit, you preserve that skill. You preserve the mechanics of your fingers, your digits.

Why she didn't become a professional musician: I just always had something else going on. And I was in a math high school as well. In Moscow, you have to make the decision whether or not you're going to be a professional when you're 14. It's very young, and I wasn't ready for that.

Musical highlight of her life: When I lived in the Bay Area, I was the principal pianist for the Redwood Symphony. I got to play Brahms's second piano concerto with them and that was probably the highlight of my whole career. It was amazing to play. That's a monumental piece. And it's so beautiful.

How music helps her be a better scientist: It allows your mind to relax. We're all of us type A, overachieving academics. We're constantly thinking about work and about our students and about proposals. When you play the piano, it allows your mind to let go. It's just me and the universe and the music.

Read more about Caltech's musicians and hear their music at **magazine.caltech.edu/post/striking-a-chord**

Grid Guru

This Caltech alum relishes constructing crossword puzzles for many of the same reasons he appreciates computer science. Publication in *The New York Times* is a bonus.

by Judy Hill

Steve Ginzburg (BS '98) was only a few years post-Caltech when he caught the crossword bug. On a trip home to Santa Cruz to visit his parents, Ginzburg, who was working as a software engineer in Santa Barbara at the time, was intrigued by the puzzles his empty-nester parents tackled at breakfast.

It was not the challenge of solving the clues that held his attention, though. "I thought about it for a few minutes," he remembers, "and I realized, 'You know what, these are probably more interesting to create than they are to solve.'" With that, he grabbed a piece of graph paper and started make his own puzzle.

Humbled by the difficulty of the task, Ginzburg contacted "a very active, supportive community of crossword puzzle constructors" and found a couple of puzzle veterans who coached him by email. In 2006, he had his first puzzle published in *USA Today*. The following year, one of his puzzles was accepted by legendary puzzle editor Will Shortz and published in *The New York Times*, the gold standard for crosswords.

Other newspapers, including the *New York Sun* and the *Los Angeles Times*, have published his puzzles over the years, and though the puzzle pursuit has taken a back seat to parenthood and his work to improve safety-critical automobile software, Ginzburg is as much a crossword puzzle fan as ever. He attributes much of that interest to his training in computer science.

"Filling a grid with interlocking words is a very interesting problem from a computer science perspective," he says. "It comes from a class of problems where there is no guarantee of a perfect solution. And so you have to use heuristics; you have to apply intelligence to it to try to find a solution that you know isn't going to be optimal but is going to be pretty good." This, he says, is where the artistry of crossword puzzle creation meets the science of computer science.

For Ginzburg, the real pleasure in both solving and constructing a crossword puzzle lies in the theme, the clever idea or piece of word trickery that unites a puzzle's longest answers.

"It's really the most critical part of the puzzle, certainly if you want to create a marketable puzzle," says Ginzburg. "If it's a daily puzzle, you need to come up with three or four or five themed answers that are all consistent and fit together and make sense. For a Sunday puzzle, which is larger, it's more like six or seven."

Ginzburg remembers having particular fun working with a theme based on phrases that start with a pair of letters in consecutive alphabetical order that are an abbreviation. "So, I had ABPOSITIVE, which is a blood type. I had VWSCIROCCO, which is a car I once drove, and UVEXPOSURE. A commentator on a blog noted that he got as far as UVEXP but then figured with that odd letter lineup something had to be wrong in the crossword, until he worked out the theme."

Ginzburg keeps a file for theme ideas that he started to think about but never used. One such idea is based on a phrase that had suddenly come into the language: fake news. "I thought, 'OK, I've got to do something with that.' Will Shortz in particular has pioneered the idea of crossword puzzles being timely and interesting and topical." Working with the idea of "kind of nonsensical" phrases, Ginzburg jotted down the following:

Clue: Shocking discovery: tiny boats paddled by sprites!
Answer: FAYCANOES
Clue: Oliver Twist's so-called boss shows his delight—you won't believe why!
Answer: FAGINOOHS
Clue: Sign of the times, if not *The Times*
Answer: FAKENEWS

"I never managed to make this into a puzzle," he notes ruefully. "I just never got the theme to work quite right. I couldn't come up with enough words or phrases that were amusing enough or the right length."

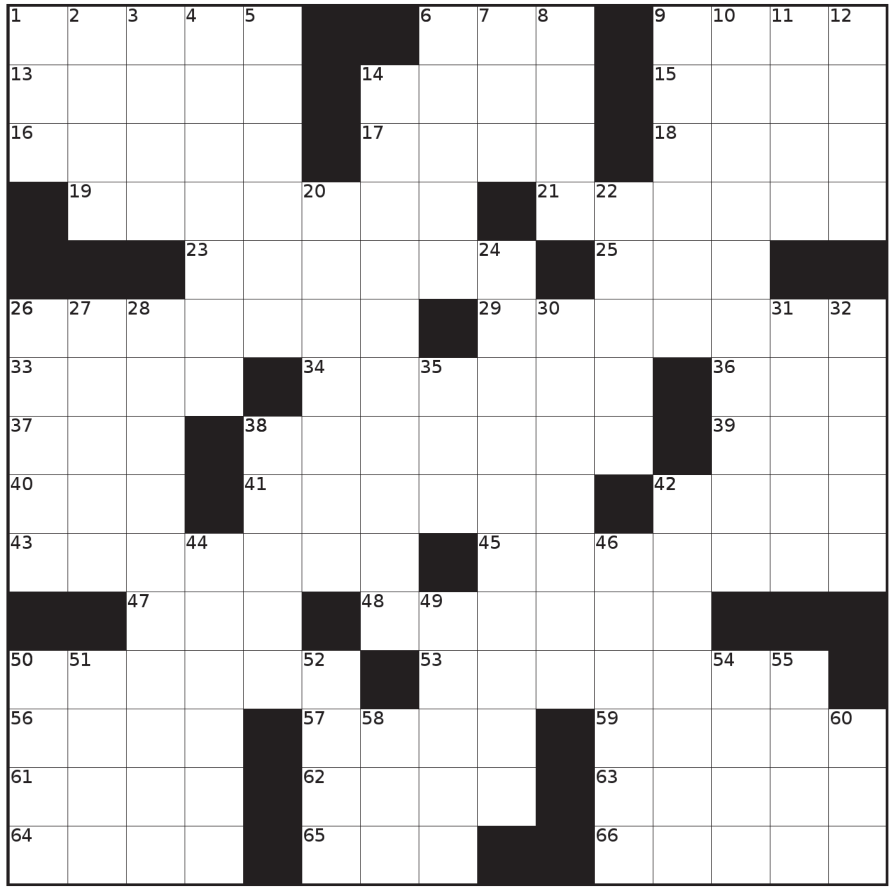
Once the theme is set, the next challenge is to create the grid and fill it with words that are reasonably well known. "Many people don't realize this," says Ginzburg, "but the difficulty in the crossword puzzle comes not from the words being obscure but from the clues being clever. That's the difference between a Monday puzzle and a Saturday puzzle [the most difficult of the week]."

Prior to the Will Shortz era, he notes, crosswords were filled with arcane words and "all sorts of crazy things that nobody had ever heard of," but now the entire industry has gone in the direction of making the puzzles more accessible, putting the burden on making the clues, the last part of the process, trickier to add a degree of difficulty.

"There's a whole art to clue writing," says Ginzburg, "and, particularly for common three-letter words, it can be challenging. Ginzburg is especially proud of one clue he came up with for the word AWL ("Spiked punch?") that even surprised his editor.

Left: Cyber security analyst Steve Ginzburg (BS '98) moonlights as a cruciverbalist.

Alums Across the Board, by Steve Ginzburg



ACROSS

1 Regina Dugan, PhD '93, former director of ___
6 Small part in a large machine
9 Org. defending freedoms
13 Like Chichen Itza
14 Start of "Deck the Halls" refrain
15 Defeat soundly
16 Spinach alternative
17 Some TVs
18 Hawkeye portrayer
19 Greet like a junkyard dog
21 France Córdova, PhD '79, NSF director and former president of ___
23 Michael Jackson hit featuring an Eddie Van Halen guitar solo
25 Order's partner
26 Steingrímur Hermannsson, MA '52, former prime minister of ___
29 About two and a half acres
33 Mare's hairs
34 Bridge combo
36 Stimpy's pal
37 Picnic spoiler
38 Harrison Schmitt, BS '57, astronaut and former ___
39 It comes from the heart? (abbr.)
40 Old orbiter
41 Ordained one
42 *Rowan & Martin's Laugh-In* comedian Johnson
43 It keeps you going
45 Sabeer Bhatia, BS '91, co-founder of ___
47 ___ -Man
48 Rain forest vines
50 Benjamin Rosen, BS '54, former chairman of the board for ___
53 Lost sleep (over)
56 ___ Prize (mathematics honor)
57 Coffee holders
59 Lackluster
61 All's counterpart
62 "Pick me! Pick me!"
63 ___ Walk
64 Annual Vietnamese holidays
65 "-com" preceder
66 Ray Feeney, BS '75, ___ winner for advancing the technology in his field

DOWN

1 Run-___
2 Contented sighs
3 Clancy hero
4 Teaching story
5 Tenor Bocelli
6 Some low-water plants
7 Out-of-date
8 Sound of surprise
9 Landing place of Noah's Ark
10 It ended around 1990
11 Big Island bash
12 ___ Reader: alternative media digest
14 "No way, no how!"
20 Camper's light
22 Bad gut feeling?
24 "What a mean thing to say!"
26 Islamic leaders
27 "Enough!"
28 Sting victim's court defense, perhaps
30 Transition area between plant communities
31 Prefix with linear
32 Actress Georgia of *Everybody Loves Raymond*
35 Aye's opposite (Scottish)
38 Shining light in Virgo
42 Dutch beers
44 Syrup sources
46 Kind of artist or parlor
49 Otherwise
50 Is incapable of
51 Double-reed instrument
52 Part of Q.E.D.
54 *Iliad* or *Odyssey*
55 Star of the opera
58 It sometimes represents density
60 Article from Germany?

Find the answers to Ginzburg's crossword at **magazine.caltech.edu/crossword**

Though most crossword constructors today use grid-filling software, Ginzburg insists it does not make creating a crossword less challenging. "Grid-filling software will tell you, first of all, if your grid is fillable. It will also help you figure out possibilities, like, 'Here are half a dozen different words that could fit in this slot.'" Still, he says, even with the software, there have been times when he has had 90 percent of the puzzle filled but then found himself backed into a corner. He says, "I have to use this really awful word up in the northeast corner in order to finish it. So, do I put that in there and hope the editor lets me get away with it, or do I come up with a clever clue, or do I unwind three quarters of the puzzle and start over and pursue a different direction?"

This, Ginzburg says, is where heuristics play a role in filling the grid. "A computer program is not going to give you heuristics. There has to be human intelligence applied to it to try to come up with the best possible grid. If not, an experienced editor will look at it and say, 'You know what? This has garbage entries.'"

An example of a "garbage entry" might be something like the word OREO, which, as any cruciverbalist (or crossword puzzle expert) will lament, pops up frequently as an answer. Why is that? There are certain combinations of letters, says Ginzburg, that are "just really handy" for filling a grid. "Anything that involves low-Scrabble-score letters, lots of vowels, or odd abbreviations."

Most words in the English language, he elaborates, alternate consonants and vowels. "So, if you ignore consonant sounds that are made up with two letters, like CK, and you just think about single-letter sounds, in order to fill a square, you have to alternate words that start with a consonant or a vowel. So, in a crossword puzzle, you're going to find more words that start with vowels than you would in ordinary text, and those words are going to be used more often. And that's how you end up with words like OREO and ARIA being overused."

The number of venues for selling crossword puzzles has diminished over the years, says Ginzburg, partly because fewer people read newspapers. And although he has less time to devote to it, solving puzzles will always be a favorite pursuit for Ginzburg: "I enjoy it more now that I've had the chance to create a lot of puzzles and because I appreciate more the artistry that goes into them."

As father of a 7-year-old and a 5-year-old, Ginzburg also gets a kick from hearing them start to make puns and experiment with wordplay. "It's like, 'Yes! They picked up the gene!'" [C]

In Memoriam

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

Walter Munk (BS '39, MS '40), 1917–2019

Alumnus Walter Munk, often called the "Einstein of oceanography," passed away on February 8. He was 101 years old.

Munk's early research on quantitative prediction of surf conditions was instrumental in ensuring the success of Allied amphibious landings during World War II. As a professor of geophysics at the Scripps Institution of Oceanography at UC San Diego, in La Jolla, he pioneered the use of sound waves for studying the ocean's structure, demystified the phenomenon of tidal locking, and led a global study of sea temperature that demonstrated conclusively the reality of climate change.

Possessed of a gift for translating observations of nature into profound quantitative descriptions, Munk laid the foundations of modern physical oceanography. A maverick who championed brave, revolutionary ideas, Munk was the first to understand the influence of tidal forces on the rotation of planets, was the first to use power spectra to describe waves, and was one of the first scuba divers on an oceanographic expedition.

"Walter was a legend in the field. I can hardly get through a couple lectures in my introduction to oceanography course without mentioning one of his major contributions," says fellow oceanographer Andrew Thompson, professor of environmental science and engineering at Caltech, who earned his PhD at Scripps. "It was a privilege to meet and talk with Walter as a graduate student and to see, firsthand, his love of science."

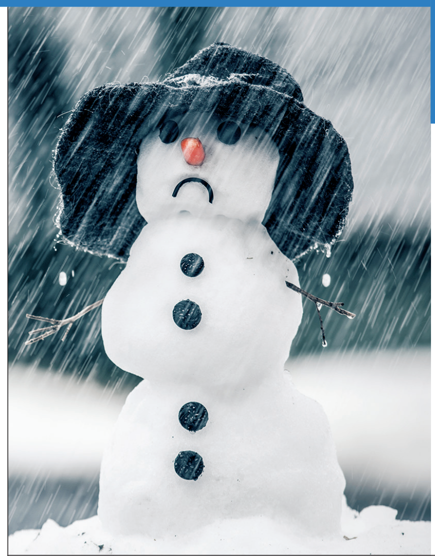
Even decades after his official retirement, Munk remained involved in research and scientific advisory efforts. He published his last peer-reviewed paper in 2015 at age 98 and, in that same year, participated in the Vatican City conferences on climate change attended by Pope Francis. He held the Secretary of the Navy/Chief of Naval Operations Oceanography Chair at Scripps until his death.

Endnotes

What common scientific misconception would you most want to correct?

That natural and "organic" products do not contain chemicals.

Ronald Hodges (PhD '78)
PALO ALTO, CA



The misconception that cold weather locally means that the climate is not warming globally.

Ivar Tombach (BS '65, PhD '69)
CAMARILLO, CA

The misconception that there is a link between vaccinations and autism or autism spectrum disorders. This false belief has resulted in the recurrence of debilitating and potentially fatal diseases, and could lead to epidemics.

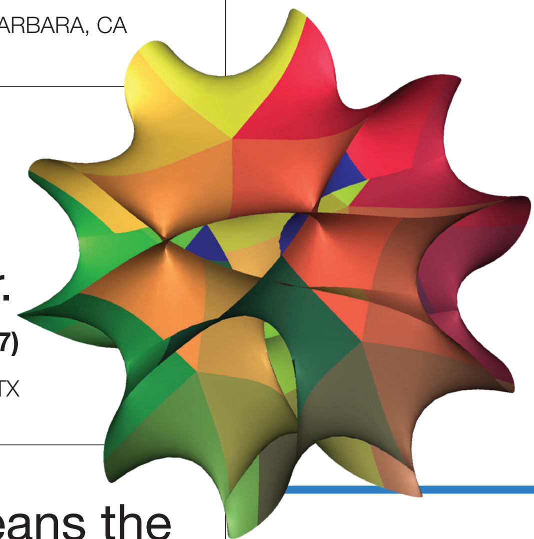
Fran Finney (BS '76)
SANTA BARBARA, CA

That a Parsec is a speed, not a distance.

Alice Tang (BS '79)
MORAGA, CA

That the number of dimensions of reality is a small, finite number.

Paul Sobel (MS '67)
AUSTIN, TX



A 2-D cross-section of the 6-D manifold known in string theory as the Calabi–Yau quintic.

The misconception that there is a dark side of the moon. In truth, there is only a far side. Causes much confusion.

David Drake (BS '74)
ESCONDIDO, CA

* Our sun is classified as a "yellow-type" star, but it's actually white. People depicting the sun as yellow isn't a *serious* misconception, but it irks me.

Jessica Davis (BS '12)
DUNEDIN, NEW ZEALAND

That "A implies B" means the same as "B implies A" (which includes the misconception that correlation is equivalent to causation).

Michael Wilson (BS '77)
HINESBURG, VT

I think there are misconceptions about the methods and goals of science. Science isn't a bag of facts; it's a way of thinking and observing that helps sift evidence for and against theories.

Richard Yeh (BS '98)
BROOKLYN, NY

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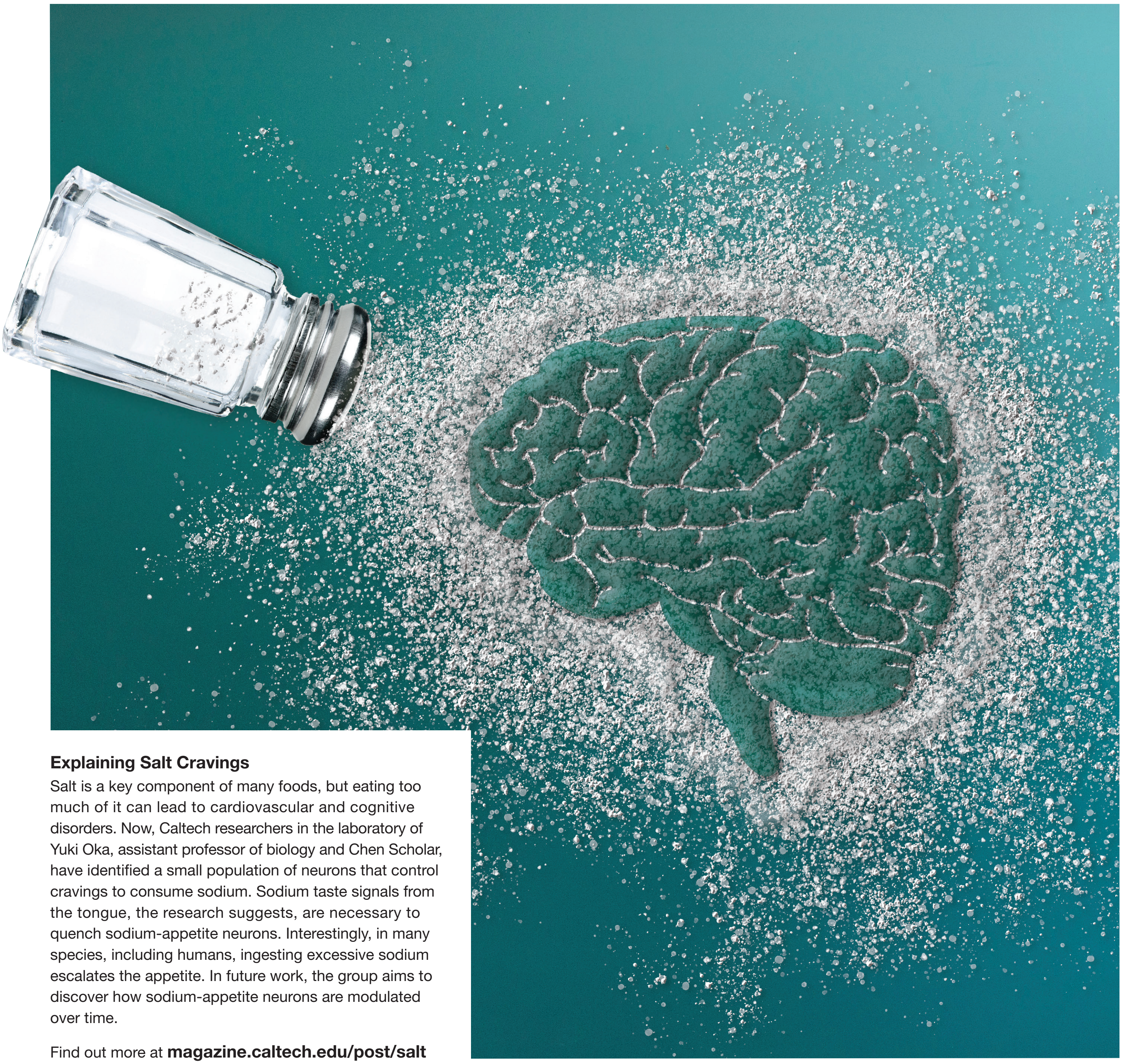

Explaining Salt Cravings

Salt is a key component of many foods, but eating too much of it can lead to cardiovascular and cognitive disorders. Now, Caltech researchers in the laboratory of Yuki Oka, assistant professor of biology and Chen Scholar, have identified a small population of neurons that control cravings to consume sodium. Sodium taste signals from the tongue, the research suggests, are necessary to quench sodium-appetite neurons. Interestingly, in many species, including humans, ingesting excessive sodium escalates the appetite. In future work, the group aims to discover how sodium-appetite neurons are modulated over time.

Find out more at **magazine.caltech.edu/post/salt**