Spring 2019

Caltech magazine

On a path to discovery: *Drosophila* research is leading the way

Also inside:

How do planets take shape?

Titan's massive dust storms

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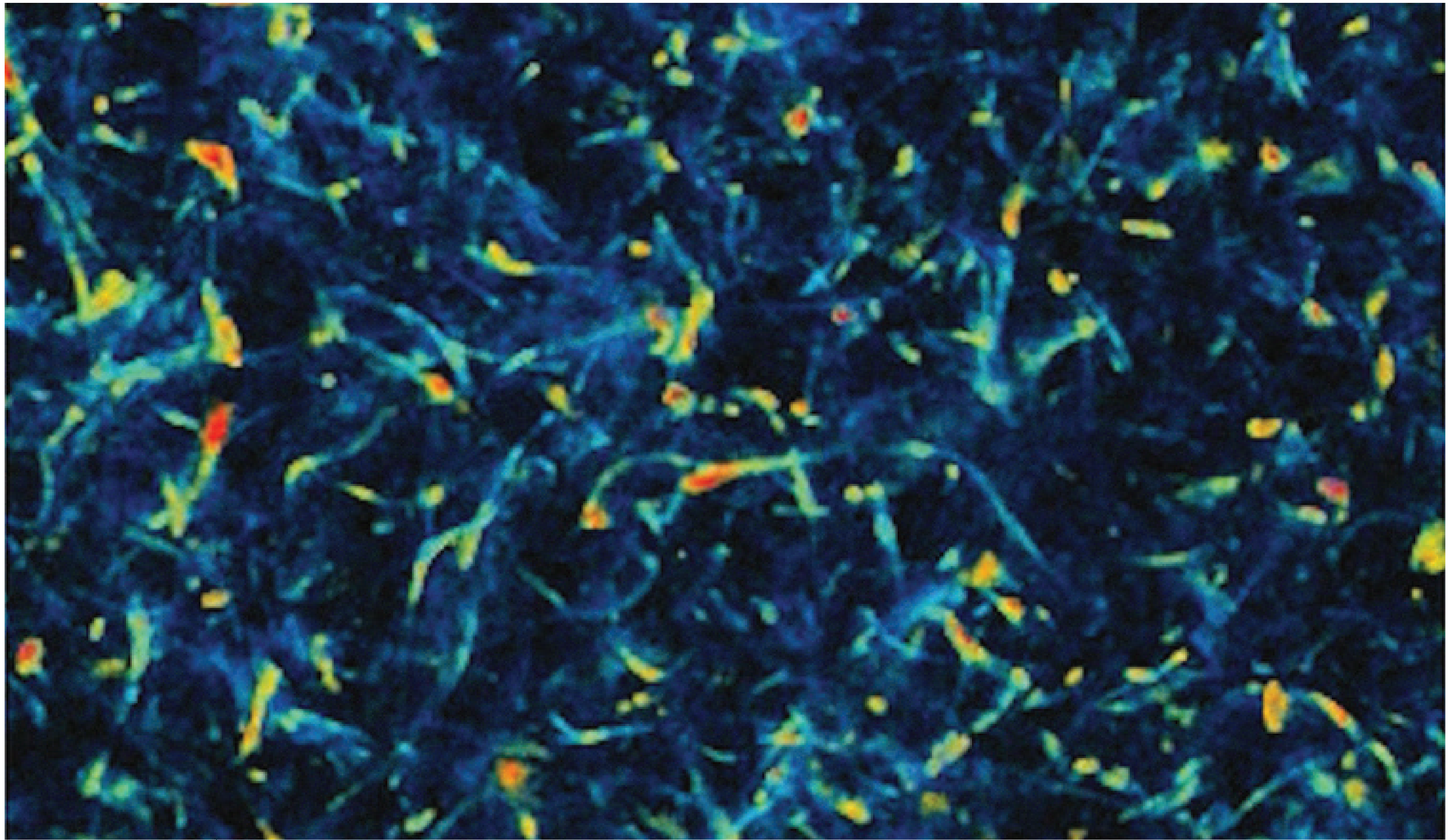

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Left: This artist's concept shows a burgeoning planetary system. See article on page 22.

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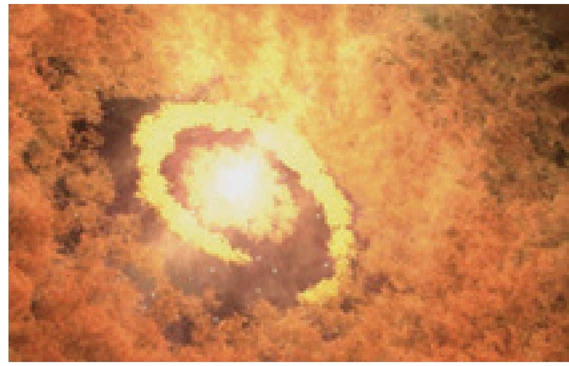

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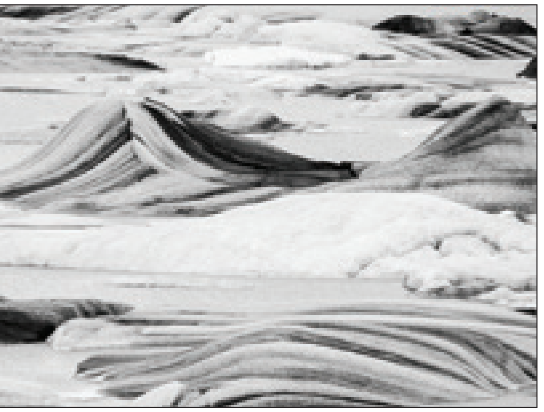


Above: *Floating Ice with Ash Layers: Iceland,* a photograph by geology postdoc Flavien Beaud that appeared in the 2019 GPS Calendar.

Letters

The Eyes Have It

Please convey my kudos to the reporters, writers, and editors responsible for the piece on vision-preserving medical interventions in the latest *Caltech* magazine [Fall 2018]. I write as an astro alum and amateur astronomer who coordinated some coverage of night myopia and LASIK for *Sky & Telescope* magazine a dozen or so years back. (Since then I have taught physics and astronomy, mostly at the high school level, and worked in the textbook industry.) The UV-tuneable replacement lenses could be a "killer app" for amateur astronomy; I'm curious whether they might be available on an elective basis! Anyhow, good stuff. I understand the topic more clearly now.

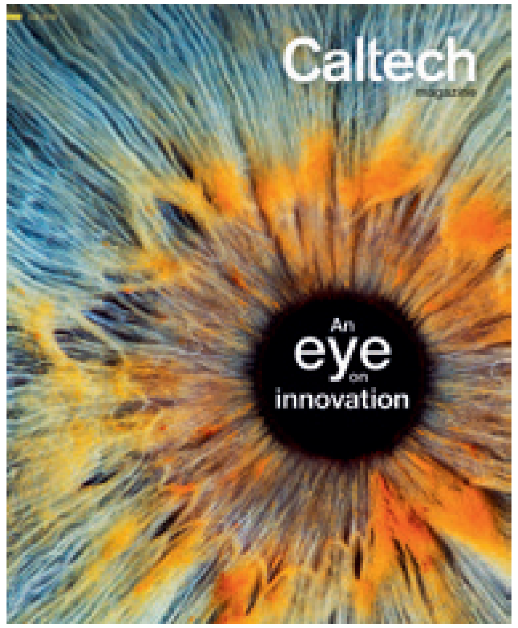
Joshua Roth (MS '91, PhD '94)

What a shock your new format presented! At first I wondered whether I'd like the new look, but became convinced it was more riveting because of all the individuals and their projects depicted.

I was particularly interested in an article in the Fall 2018 issue: "An Eye on Innovation." It reminded me of an invention my late husband, John C. Evvard (PhD '73), had patented back in June 1973, and which seems to me like the precursor of the laser equipment now in use. He was an associate director at the NASA Research Laboratory near Cleveland, Ohio, and had many other inventions that were patented by the government.

Thank you for continuing to send me your Caltech publication.

Jean L. Evvard



Fun for Every Age

I am an alum and a parent of a toddler. I just wanted to thank you for making such a quality magazine for such a broad audience. My kid loves the big faces, the colorful art, and searching for his favorite things in the detailed historical photos. I appreciate how the pages are burly enough to be toddler-proof. When my parents visit they learn about Frances Arnold and Richard Feynman and can be proud all over again of where I went to school. It's a perfect coffee table conversation starter for all visitors ("Is Jupiter hot?"). Please keep doing what you're doing; it is a big hit with my family.

Eva Rose Murdock Balog (BS '06)

Staying Connected

I was delighted to get the latest issue of *Caltech* magazine. It always surprises me how much I get out of it: it allows me to feel, in some small way, as though I am still part of the Caltech community, even though I have not been able to visit in years.

Luke S. Sollitt (MS '99, PhD '04)

"With the kind grace of the geology faculty, I took that course a decade later, so a mailman handed me my diploma in 1971."

Start with the facts

With great pleasure and thanks, I send you my book *Tragic Truth*, inscribed to the staff of your excellent magazine, which regularly reminds me of the wonderful institute that shaped my mind so I could write it, more than 50 years later.

A BS in geology should have crowned my 1956–60 undergraduate residency, but in my senior year I did not complete the required course in German, instead spending afternoons founding start-up electronics firm Colorsound, Inc. With the kind grace of the geology faculty, I took that course a decade later, so a mailman handed me my diploma in 1971.

Taught by a constellation of Nobel laureates including Beadle, Feynman, and Pauling, and lesser-known but world-class geologists Allen, Kamb, Lowenstam, Richter, Sharp, Silver, Taylor, and Wasserburg, I learned to start with all relevant hard facts, then hypothecate and analyze before reaching a conclusion.

Pierre Sundborg (BS '71)

SoCaltech

- Caltech's new equity office
- Visual culture joins the curriculum
- Unearthing hidden tech treasure
- A new campus center opens its doors

Caltech's Newest Nobel Laureate

Hundreds of members of the Caltech community, along with local elected officials, gathered along the Olive Walk on November 8 to honor Frances Arnold, who received the 2018 Nobel Prize in Chemistry for the "directed evolution of enzymes."

During the ceremony, Arnold, the Linus Pauling Professor of Chemical Engineering, Bioengineering and Biochemistry, told the crowd she felt "incredibly lucky and grateful" to have worked for more than 30 years at Caltech, "a very small and special institution that made it possible for me to do the work that led to the Nobel Prize."

Arnold, who is also the director of the Donna and Benjamin M. Rosen Bioengineering Center, added, "Only here could I convince students from very different disciplines (engineers, chemists, biochemists, molecular biologists, and computational scientists) to throw their hat into this ring and this completely unexplored field, and contribute their creativity to this kooky idea that you could breed proteins like you can breed cats and dogs. And only here would I have been challenged to solve ever harder problems."

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

Five Questions for:

April Castañeda

April Castañeda, recently appointed to the newly created position of assistant vice president for equity and equity investigations and Title IX coordinator at Caltech, will design and implement a comprehensive approach to all issues pertaining to discrimination, unlawful harassment, and sexual misconduct. Though the role is new for both the Institute and Castañeda, she is no stranger to campus, having served in a variety of roles at Caltech for more than 20 years before spending two years as the assistant director for human resources at JPL.

1. What motivates you to do this work?

I've spent most of my career doing things that are engaged around social justice. It's important to me that people have the rights and the ability to do good work.

When I first came to Caltech, I was reluctant to be an intern here because before then I had always worked with underserved populations, and here I saw a lot of privilege. My adviser at the time said to me, "April, pain is pain, no matter if it's in a suit or on the street." And she said, "You have to decide. If you're trying to alleviate pain and help good things happen, there's a place for you here."

2. How is your office different from the former Title IX office?

The office now includes not just Title IX [a law that covers discrimination on the basis of sex] but also Title VII and Title VI, which cover discrimination based on race, color, religion, sex, and national origin. We also have state regulations, and California has about 40 different protected classes. So anything that involves a protected class comes into this office.

3. How have things changed now that the office is part of HR rather than Student Affairs?

Although the office is now part of HR, we maintain very close connections with Student Affairs, working closely with the vice president, the deans, and the many other offices that serve our students. We've also hired an education and deputy Title IX coordinator for Student Affairs to ensure that the needs of the student community are met.

4. How do you encourage people to come forward in a way that feels comfortable for them?

My approach is always that it is a privilege to be there in a person's life at a moment when they really need help, so I try to handle it with care and respect. The person who's reporting the incident has a lot of ability to dictate what happens. They often can come in and file a report without us taking action. I follow where they lead. That said, there are things we have to move on if we feel like there's a danger to the community or someone is a danger to themself.

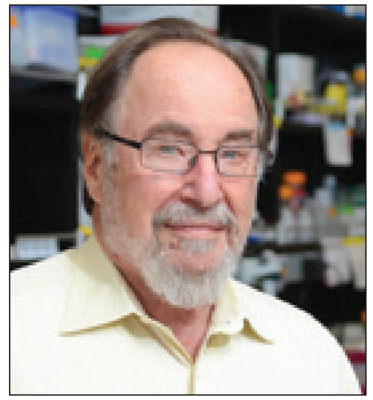
5. What does success look like for the equity office?

I'll know it's successful if the number of our cases goes down and the number of our office visits goes up. I want people to come in before things escalate. Absolutely there are times when we need to do an investigation, but there are also lots of things that we can do to build inclusive communities. We want people to worry about school, work, their research, winning Nobel Prizes. We don't want them to worry about, "Am I safe? Am I OK?"

Read the whole interview at magazine.caltech.edu/post/april-castaneda

"The general worry is that if we develop the ability to modify the germline, only wealthy people will be able to take advantage of that, and so it may exacerbate the difference between the opportunities available to the wealthy and the impoverished."

David Baltimore, *Caltech president emeritus and Robert Andrews Millikan Professor of Biology; chair of the Second International Summit on Human Genome Editing, held in November 2018 in Hong Kong*



CS+X

where X =

What happens when you take computational science (CS) and combine it with another discipline? That was the question Adam Wierman, director of Information Science and Technology at Caltech posed last year at a kickoff event for a new initiative called Caltech Computes: Disrupting Science and Engineering with Computational Thinking. His answer? Something new and disruptive. The goal of the initiative is to bring together faculty and students from across campus for seminars and workshops, to create courses and educational programs in "CS+X," and to seed research in emerging CS+X areas too new to receive support from external grants. Here are some examples of how CS is being combined with different disciplines at Caltech.

Medicine:
Developing a prosthesis that can use machine learning to help patients with spinal injuries stand again.

Nature:
Distinguishing individual bird and tree species using a combination of machine learning and expert human input.

Astronomy:
Searching for supernovas by scanning enormous data sets gathered by sky surveys.

Biology:
Using DNA origami to create a real-life version of "Hermione's bag."

Physics:
Exploring how quantum mechanics can be utilized to create unbreakable cryptography.

Economics:
Improving the algorithms that govern the way doctors are matched with hospital residencies, kidneys with donors, and children with public schools.

Chemistry:
Paving the way toward more efficient and less volatile lithium-ion batteries.

Visualization:
Applying algorithms from quantum mechanics to generate computer-simulated fluids.

Energy:
Using algorithms to govern electric-vehicle charging, reducing the need for a vast charging infrastructure.

BRAIN Power

19

Number of BRAIN grants from the National Institutes of Health received by Caltech in the four years of the program, the second highest for any institution (only Stanford has received more)

$22

Million total

14

Caltech faculty members as principal investigators

5

Caltech divisions represented

Research has included:

- Using non-invasive methods such as ultrasound and light to stimulate or suppress individual neurons
- Tracing the wiring of brain circuits that control movement, emotion, and thirst
- Developing brain-machine interfaces to help quadriplegic people regain motor function

Class Act:

Visual Culture

A new visual culture program is about to make Caltech a lot more colorful. From tours of neon art around Los Angeles to campus artists-in-residence, the program will offer something for anyone interested in art and its potential for intersecting with science.

Funded by the Andrew W. Mellon Foundation and still in the planning stages, the program will be part of the Division of the Humanities and Social Sciences (HSS) and will include new course offerings, a postdoctoral instructor, artists-in-residence, guest lecturers, and the addition of a visual culture professor to the faculty.

Soft launch

English professor Dehn Gilmore, who is overseeing the program's launch, says this academic year is a pilot for the program, but adds that there is already a full slate of activities planned for the next several months, including a student trip to the Los Angeles County Museum of Art (LACMA) to see a 3-D-themed exhibit.

Visitors to campus will include Malian textile artist Abdoulaye Konaté; Katherine F. Chandler, a professor and artist at Georgetown University whose work has explored, among other things, drone aircraft and drone warfare; and Scott Chimileski, a microbiologist and photographer of microbial life.

Stay awhile

A centerpiece of the program will be an artist residency that brings artists for extended stays on campus to work with students and organize exhibits and other events, including public lectures. "This will be an opportunity to bring in numerous artists to develop deeper conversations and collaborations and cross-pollinate

ideas," says Hillary Mushkin, research professor of art and design in mechanical and civil engineering, who co-directs Caltech's data visualization program and is involved in shaping the artist-in-residence program.

The first artist-in-residence will be Leslie Thornton, an experimental filmmaker best known for *Peggy and Fred in Hell,* a 17-episode series that follows two children acting out lives as adults in a chaotic world.

Creative collaborations

Other Caltech faculty members involved in the visual culture program are Professor of English Catherine Jurca, who studies classic Hollywood cinema and the American novel, and history professor Nicolás Wey-Gómez, whose lecture series Exploration: The Globe and Beyond will be expanded as part of the program.

The program will also involve collaborations with The Huntington Library, Art Collections, and Botanical Gardens that connect the Caltech community with artists, exhibition culture, scholars of visual culture, and The Huntington's extensive collections of visual materials.

"It will be very exciting for undergrads to learn new ways of thinking and looking," says Gilmore. "I think that will inspire new research avenues and hopefully inspire a new set of conversations among the faculty."

> "We hit the Martian atmosphere at 12,300 mph, and the whole sequence to touching down on the surface took only six-and-a-half minutes. During that short span of time, InSight had to autonomously perform dozens of operations and do them flawlessly. And by all indications that is exactly what our spacecraft did."
>
> —*InSight project manager* **Tom Hoffman**

InSight Principal Investigator Bruce Banerdt, left, and Hallie Gengl, data visualization developer, celebrate InSight's Mars landing on November 26.

Object Lesson: Historic Hardware

Caltech is a treasure trove of vintage computing equipment … if you know where to look. "You see these e-waste piles all around campus and people just stick old equipment in them," says Albert Tseng, a sophomore majoring in computer science. "Most of it is actual waste, but sometimes you find really interesting things being discarded."

Tseng teamed up recently with fellow sophomore Hongsen Qin, whose particular passion is old keyboards. The pair recruited junior Karthik Karnik and, together, the three undergrads turned their hobby into a new student club dedicated to preserving, collecting, and showcasing vintage computing hardware used on the Caltech campus.

Through word of mouth and social media, the Vintage Computing Club has garnered interest from a broad swath of students and alumni. Labs around campus are starting to contact the group about "old computers sitting in attics," says Tseng, who notes that many of these computers were integral to the history of their former labs or to the history of Caltech. "We're finding these rare workstations that were very expensive at the time. And they still work!"

Beyond the thrill of unearthing hidden tech treasure, the trio's goal is to gather enough items for a campus exhibit along the lines of Paul Allen's Living Computer Museum in Seattle. To that end, they are restoring the machines that come to them, keeping the patina of age and the Caltech property tags but making them operational. As Tseng says, "It's no fun just seeing something behind a glass case."

The club's broader aim is to begin to document computing at Caltech through the decades. "We're looking at the history of different labs, different research groups," says Qin. "We're showcasing them because it's an important part of Caltech history."

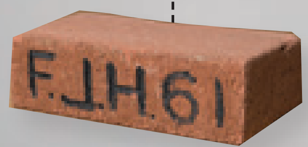
Pictured above is an IBM Selectric typewriter, one of the most well-known pieces of office and computing equipment of the 20th century. Machines such as this one (which came from the applied physics department) were used at Caltech as makeshift printers and for terminal keyboards. Although quite complex, with more than 1,000 parts, they were remarkably reliable and rarely broke down. The design of the Selectric allowed the user to switch typeballs for different fonts as well as math symbols and other characters.

See more vintage finds at magazine.caltech.edu/post/historic-hardware

New on Campus: The Hameetman Center

In late February, the Caltech community will have a new place to gather. The Hameetman Center, named in honor of Caltech trustee Fred Hameetman (BS '62) and his wife, Joyce, features a large public lounge, an expanded Red Door Marketplace, the Caltech Store, music-rehearsal facilities, student-club rooms, a multipurpose room, and a conference room. The rehearsal space is made possible by a gift from Steven Frautschi, emeritus professor of theoretical physics, and his wife, Mie.

An earlier student hub known as the Dugout (opened in 1924) featured a fireplace built with the proceeds of a fundraiser in which engraved bricks were offered for a dollar apiece. The fireplace wall, composed of bricks bearing names of students, clubs, and donors, has been incorporated into the Hameetman Center on the Olive Walk side of the building.

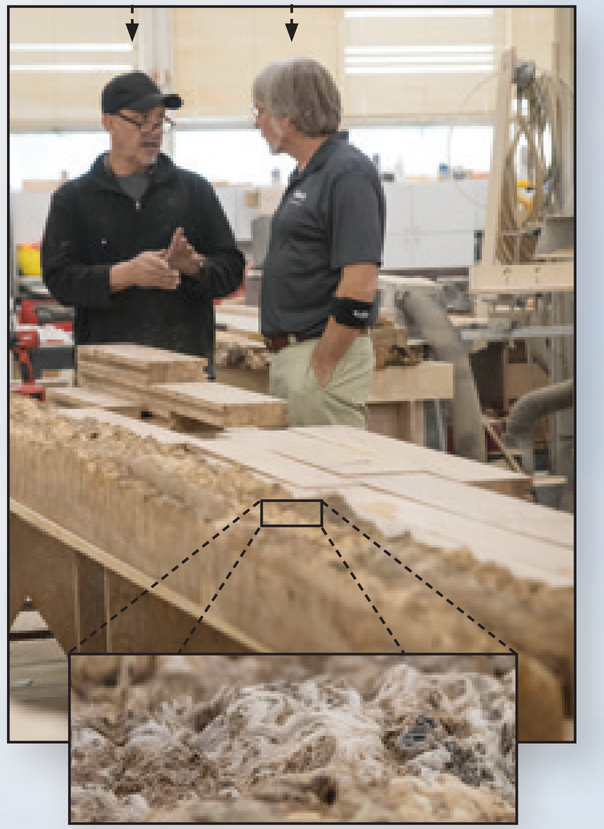


On February 28, a final brick, honoring the Hameetmans, will be placed in the center of the wall at a special dedication ceremony.

This bas-relief terracotta beaver, now located on the main staircase landing wall, was originally created for the Winnett Student Center by sculptor Albert Stewart (1900–1965).

Carpenter Francisco Estrada

Carpenter Shop Supervisor Ed Rhoads



Though the venerable Engelmann oak that stood for more than 350 years between Dabney Hall and Parsons-Gates succumbed to disease two years ago, its memory will live on in the Hameetman Center. Ed Rhoads, manager of Caltech's architectural shops and trades, in collaboration with davidkremers, who serves on the campus arts committee, has designed a 24-foot table for the Red Door Marketplace using wood from the tree. The two long edges of the table will follow the natural shape of the wood, forming what is known as a live edge.

Shreyas Vissapragada
(second-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. Shreyas Vissapragada is a second-year graduate student studying planetary science. In addition to studying the formation of rings around small solar-system bodies and using Caltech's Palomar Observatory to explore the chemistry of exoplanetary systems, Vissapragada is searching for an unknown molecule in Venus's atmosphere.

"In the planetary atmospheres class I took with Andy Ingersoll, we learned about this unknown molecule that absorbs UV light that is present in Venus's atmosphere. The fact that there's still a molecule in Venus's atmosphere that we don't know about was kind of just baffling to me. I mean, it's right next door! So I was reading up on it, and I came across a hypothesis for what this molecule could be that I thought looked fairly plausible. I realized that it was observable with ALMA [the Atacama Large Millimeter/submillimeter Array], which is used mostly for problems outside our solar system. So I was like, 'Why not?' I took this idea from class and turned it into one of my graduate research projects. It was a scientific whirlwind to put together the proposal to use ALMA because it was the first proposal that I had ever written myself. When it got approved by ALMA's scientific committee, I was expecting to feel such joy. But I remember feeling so scared that I messed up a calculation or something until I talked to a fellow grad student in the department who said something to the effect of, 'Don't worry if you got a calculation wrong. You're going to have fun and learn a lot.'"

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

In the Community

A New Home for Caltech's Rock Stars

This spring, members of Caltech's Braun Athletic Center with lofty ambitions will have access to a brand new bouldering cave: a training ground for the surprisingly large number of rock climbers in the campus community.

The bouldering cave is a room lined floor-to-ceiling with climbing holds. Some of its walls are tilted in at overhanging angles, while the floors are lined with soft mats. A resource for rock climbers to train for strength and endurance, the new cave was designed by members of the Caltech Alpine Club, a student-run organization whose membership comprises hundreds of students, staff, and faculty.

"We wanted to make it a safer and more accessible space for the club and new prospective users," says Joe Jordan, assistant director for athletic facilities. "The old cave was put together a long time ago and contained narrow passages that were not up to current standards, so it wasn't as safe as it should have been."

Postdoctoral researcher Katha Urmann and her husband, research engineer Eitam Shafran, took the lead in redesigning and building out the new space. The pair had been responsible for the route setting and maintenance of the old cave. "So when they decided they needed to shut down the space last summer, we got together with a couple other members of the club and created a plan for a new structure oriented on the old layout," Urmann says. New additions include a board for building finger strength and steeper overhangs.

Built by the Caltech Carpenter Shop, the new cave replaces the original built by Rudy Hofmeister (BS '87, PhD '93). Hofmeister built that cave on the east side of Brown Gym over the course of a week in the summer of 1990, well before climbing gyms were commonplace.

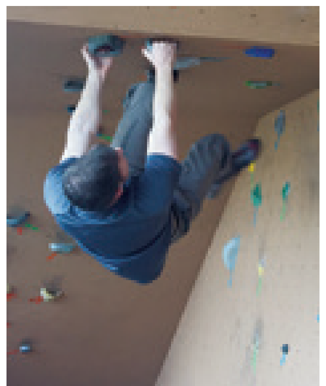
"There was a gym just opening up in Long Beach, and Hangar 18 [in Upland] was around, but other than that you either had to drive to a crag or know someone who had a homemade gym in their garage," Hofmeister says.

He used silica sand and epoxy climbing holds custom made by famed '70s-era climber Tony Yaniro, which would later inspire commercially sold production molds, according to Hofmeister. The new cave will reuse most of the old Yaniro-made holds, Urmann says; the only ones that were discarded were those that were broken from decades of wear and tear.

Other Alpine Club activities include weekly speakers (with pizza and beer, sometimes sponsored by the Southern California Mountaineers Association), group training courses with local guides, and a listserv where members can connect with one another for weekend jaunts to the mountains.

Graduate student Elle Chimiak, the Caltech Alpine Club's current president, credits the Institute's location as a big part of the success of climbing and mountaineering among the campus community. "Within a two-hour drive, you've got Tahquitz, Joshua Tree, Malibu Creek, and Stoney Point," she says, naming a few popular local crags. "Just look out your window on campus, and you've got the foothills right there, waiting to be hiked. It's hard not to be inspired to get outdoors."

—Robert Perkins



Read more about the Alpine Club and the history of the bouldering cave at **magazine.caltech.edu/post/bouldering**

Origins

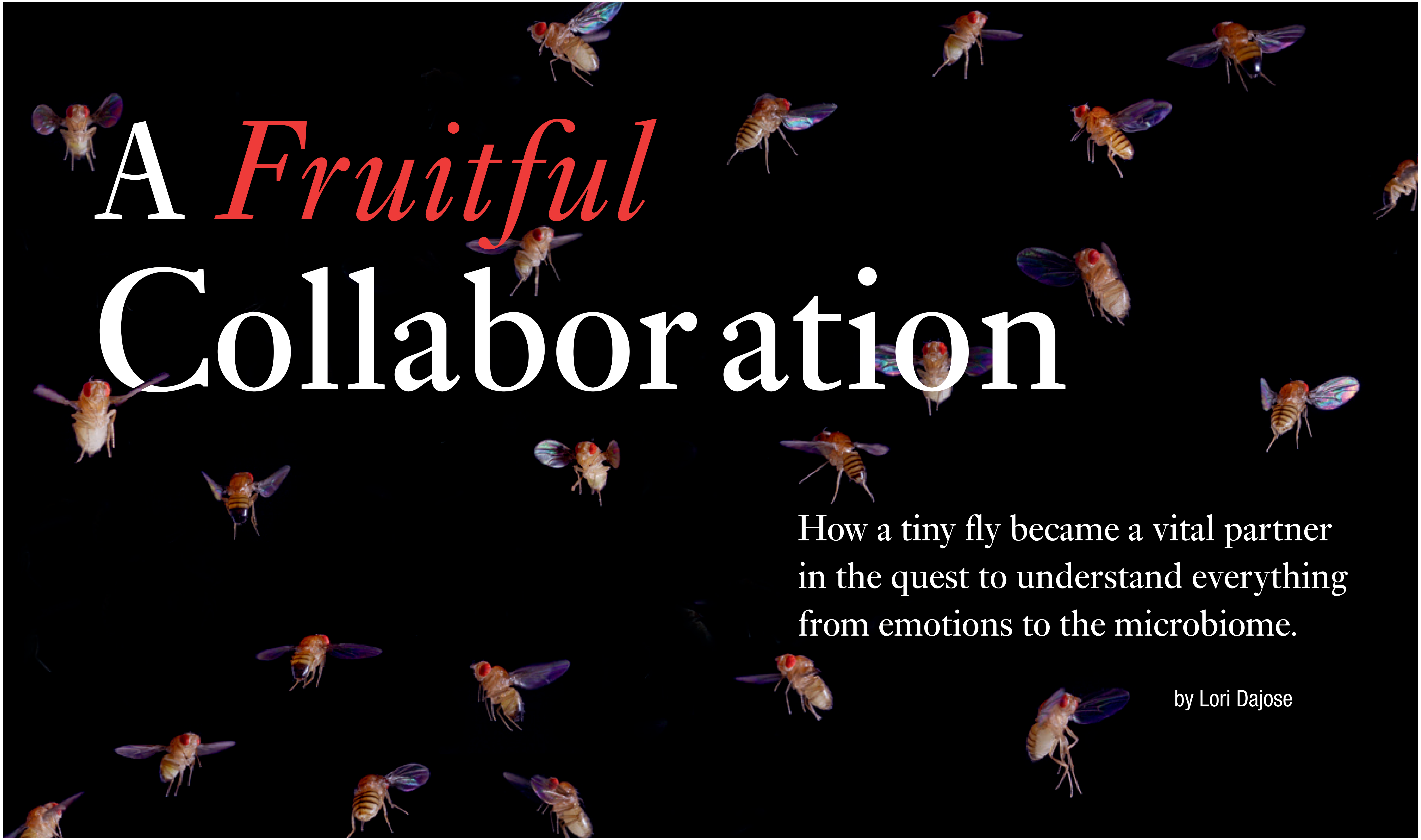
A Cache of Chemistry Models

In the 1950s, Caltech's Robert Corey and Linus Pauling (PhD '25), along with UC Berkeley's Walter Koltun, led the design of a new type of three-dimensional molecular model. These space-filling (also known as CPK) models, which became standard issue not only in laboratories but in science classrooms the world over, are made up of individual balls that represent atoms; the size of each sphere is proportional to the size of the actual atom, and its color is linked to the type of atom.

A sizable collection of CPK model components can still be found on the Caltech campus, largely due to the efforts of Larry Henling, staff crystallographer in Caltech's X-Ray Crystallography Facility. Henling has preserved drawer upon drawer of the molded-plastic atoms and their connector links as well as design drawings, contemporary photos, and correspondence related to the models.

"The models and blueprints are historical reminders of the time and effort Caltech researchers, many of whom are now forgotten, put into developing an understanding of molecular structures," Henling says. "Today, scientists do the same with just a push of a computer button."

See more molecular models at **magazine.caltech.edu/post/chemmodels**



A *Fruitful* Collaboration

How a tiny fly became a vital partner in the quest to understand everything from emotions to the microbiome.

by Lori Dajose

Hours before dawn on a Thursday morning, the scent of caramel and warm bread drifts through the sub-basement of Church Laboratory.

It emanates from a bubbling vat of viscous golden liquid in a small corner kitchenette. Peering over the concoction is Aurora Ruiz Sandoval, a Caltech employee who has been preparing this mixture at least twice a week for the past 31 years. From the aroma, it might seem that she is creating some kind of treat for hungry graduate students, but the liquid is actually food for the fruit flies (species name *Drosophila melanogaster*) that Caltech scientists use for research.

This particular day happens to be an easy one for Ruiz Sandoval: Caltech's scientists have ordered only 3,650 vials of fly food. Usually, she makes six or seven thousand vials in a single day to feed hundreds of thousands of flies.

For most people, "feeding" fruit flies is accidental, with some forgotten food on the counter summoning the tiny unwelcome guests to the kitchen. But in the laboratory, *Drosophila* are encouraged to multiply so that researchers can use them to unlock the astounding wealth of scientific information the flies hold.

Over the decades, *Drosophila* have been used in dozens of laboratories across campus as models for studying the brain, behavior, body development, flight mechanics, genetics, and more. An eighth of an inch long with round brown bodies and vivid red eyes, they may seem so far from our own species as to be irrelevant, but their simplicity makes them a powerful model organism. For one thing, they are straightforward to breed: just put male and female flies into a test tube and, 10 days later, there are new flies. Their DNA sequence consists of about 15,000 genes, all well studied and characterized. And, most importantly, a century of research on fruit flies, much of it spearheaded by Caltech researchers, has led to the development of myriad genetic tools that allow scientists to precisely manipulate individual fly genomes.

For comparison, a bacterium has about 4,000 genes while a human has over 20,000, making the fruit fly a good middle ground.

THE MAKING OF A MODEL ORGANISM

Drosophila melanogaster's relationship with *Homo sapiens* began around the time that humans were migrating out of Africa and cultivating yeast in abundance by fermenting grains and fruit to make beer and wine. Soon, wherever humans could be found drinking alcohol, the yeast-loving *Drosophila* could be found, too.

After a few millennia, the fruit flies repaid the humans, however unwittingly, by contributing their bodies to science.

Floris van Breugel, who took the photographs of the *Drosophila* flying across these pages, was a Caltech postdoctoral scholar. He is now an assistant professor in mechanical engineering at the University of Nevada, Reno.

In the early 1900s, a biologist named Thomas Hunt Morgan sought a convenient model for studying genetic inheritance and developmental biology. He came to realize that there were few models more convenient than *Drosophila melanogaster,* which could be housed in a milk bottle with a bit of mashed banana for food. Thus began a long and fruitful research collaboration.

Morgan, who arrived at Caltech to establish its Division of Biology in 1928, used the flies to discover basic principles of genetic inheritance. He had observed that one of his male flies had white eyes rather than the usual bright red eyes. Curious about how this characteristic would be passed to offspring, Morgan conducted several series of breeding experiments. He found that a fly's eye color was linked specifically to its X chromosome. Thus, he realized, a male fly (with one X and one Y chromosome) must inherit the white-eye trait from its mother, which would give the fly its X chromosome. He then reasoned that if this one trait was physically linked to a chromosome, others likely were as well.

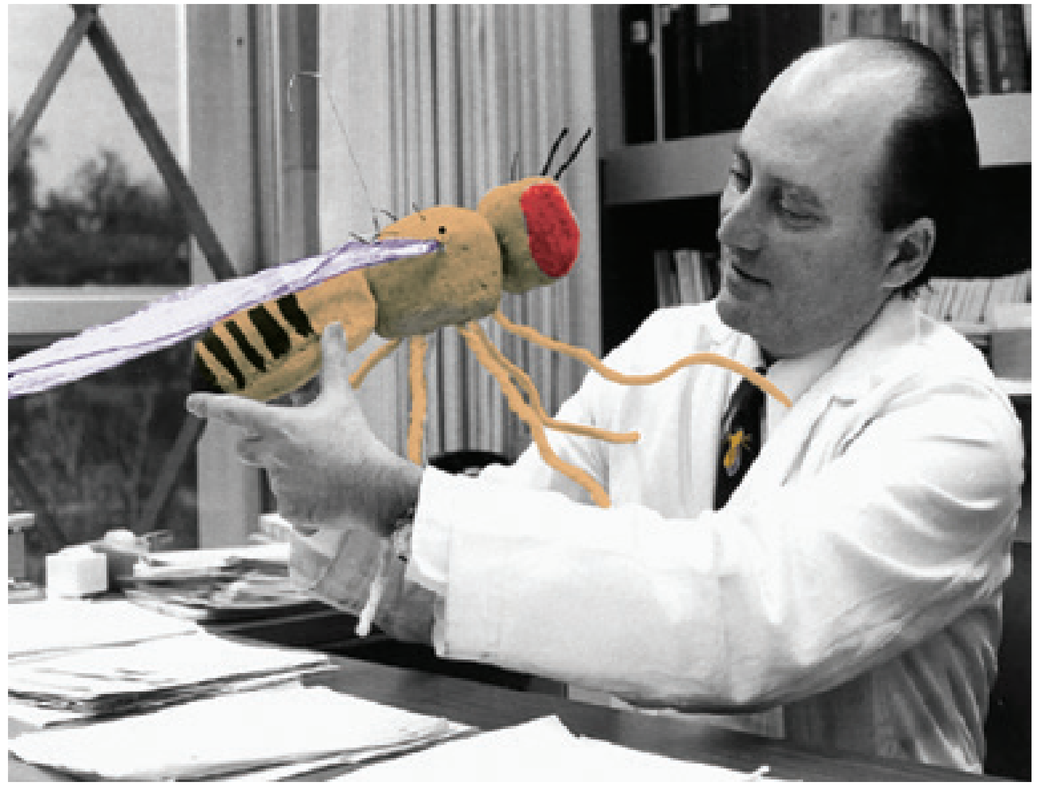
For his discovery that certain traits are linked to chromosomes, Morgan was awarded the Nobel Prize in Physiology or Medicine in 1933. His work on simple eye colors set the stage for the understanding of inherited X-chromosome-linked diseases such as hemophilia while also establishing *Drosophila* as a powerful model organism in the emerging field of genetics.

GENES AND BEHAVIOR

Caltech rapidly became known as a center for fruit fly research. In 1960, geneticist Ed Lewis (who had first come to Caltech as a graduate student to work on fruit fly genetics under one of Morgan's former graduate students) published a paper in an annual journal, *Drosophila Information Service,* detailing a recipe for fruit fly food that, he noted, resulted in quicker gestation and a higher yield of flies. The formula combined everyday kitchen ingredients, like yeast and cornmeal, with water, sugars, and a simple acid solution.

In 1988, Lewis hired Ruiz Sandoval to prepare this food. To this day, she says, the food preparation process has changed little from Lewis's original recipe.

Lewis followed in Morgan's Nobel footsteps, winning a share of the 1995 prize in Physiology or Medicine for "discoveries concerning the genetic control of early embryonic development." In that work, he had used *Drosophila* to study homeotic genes, which influence how an embryo differentiates to fit a specific body plan; for example, how the eyes, legs, wings, and other body parts form in their correct locations.



Biologist Seymour Benzer, who joined the Caltech faculty in the late '60s, in his office with an outsized (and colorized) *Drosophila* model.

Then, in the late '60s, biologist Seymour Benzer joined the Caltech faculty. Benzer, fascinated by the differences in personality between his two daughters, was motivated to examine how genes give rise to behavior. Eventually, Benzer's laboratory housed dozens of strains of *Drosophila*, each with one or more genes tweaked to give insight into a particular trait or behavior of interest. These included the *period* variant, which had an altered circadian rhythm; the *drop-dead* variant, a fly that would suddenly die; and the *dunce* variant, which was unable to learn to avoid danger.

"Experience thus far with the fly as a model system for unraveling the path from the gene to behavior is encouraging," wrote Benzer in 1971. "In any case, it is fun."

PROBING THE BRAIN

Today, much of the *Drosophila* research at Caltech focuses on probing the tiny insect's brain to understand fundamental principles of neuroscience. Building upon Benzer's work, several labs are examining how the neural circuits encoded by genes give rise to behavior. Fly brains are ideal for doing this kind of exploration because, unlike the brains of humans (which tend to be molded by our varying experiences of the world), fly brains are mostly hardwired by genes, making them constant from fly to fly.

Caltech neuroscientist Elizabeth Hong, for example, examines how scents and smells are encoded into the fly brain. "Primates like us tend to be very visual creatures, but the vast majority of the animal world relies on chemical sensing like olfaction to interact with their environments," she says.

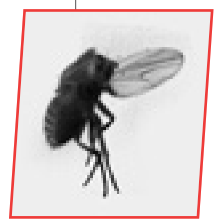
The core challenge in this area is understanding how the brain orders and encodes complex odors, from the fly-enticing fragrances of yeast growing on rotting fruit to the scents that signal the presence of a predator.

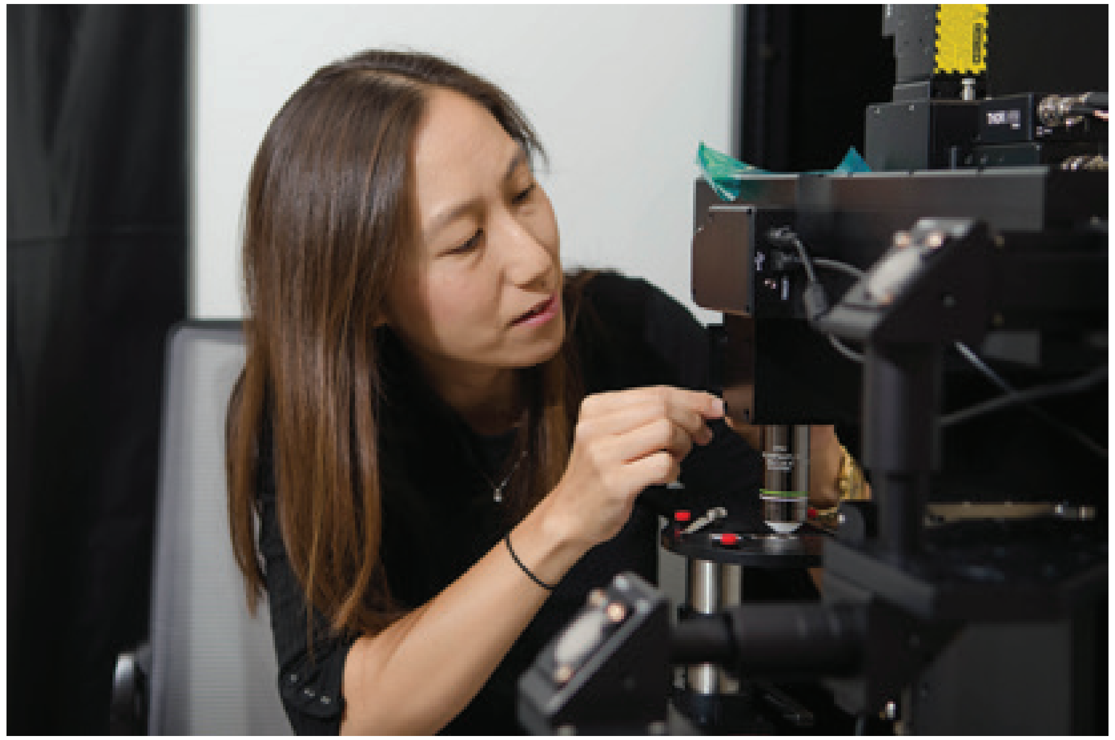
Drosophila are ideal models for studying this complex system because their brains have only about 50 unique scent receptors, the molecular detectors on neurons that recognize odors. Using the many genetic tools that have been developed for *Drosophila*, Hong and her team modify individual components of a fly's olfactory system so that they glow when activated; they then use a laser microscope that can peer deep into the living fly's brain to watch how, and where, it lights up when presented with various scents.

Compared to the mouse, which has over 1,000 scent receptors, this is a much more manageable system to work with.

Drosophila can also be used to understand the neural bases of different types of phenomena. Biologist David Anderson uses *Drosophila* in his laboratory to study how emotions and behaviors such as aggression, arousal, stress, and hunger are encoded into the brain.

Recently, the Anderson laboratory discovered a cluster of just three neurons within the fly brain that governs a so-called threat display, the specific combination of behaviors that male fruit flies exhibit when confronted with a male challenger. A fly making a threat display will throw out its wings, make rapid short lunges forward, and constantly reorient itself to face the intruder.





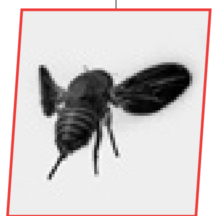
Neuroscientist Elizabeth Hong uses a two-photon laser-scanning microscope that can peer deep into a living fly's brain.

"These kinds of threatening behaviors are found throughout the animal kingdom, from fruit flies to lizards to aggressive guys at a bar, so humans may have a similar set of neurons in our own brains that generate these expressions," says Anderson. "*Drosophila* are a powerful place to start."

Although researchers can already precisely probe individual neurons and circuits, teams of scientists at Caltech are currently working to create a map of the vast web of neural connections among the fly's 100,000 neurons to learn how information flows through the brain.

While a fruit fly has about 100,000 neurons, a human has billions.

To advance that project, neurobiologist Carlos Lois recently developed a method that allows scientists to see, in real time within living flies, the flow of information between neurons. Dubbed TRACT (for TRAnsneuronal Control of Transcription), the technique uses genetically modified *Drosophila* whose neurons have been engineered to produce fluorescent proteins when sending an electrical or chemical signal. Any neuron that receives the signal and its accompanying protein will then produce its own differently colored fluorescent protein.



With this technique, researchers can observe and map the colorful glow of neural connections and how those relationships change over time as the fly grows, moves, and experiences its environment. TRACT, Lois says, could be used to determine how different diseases perturb the brain's circuits or to monitor how these circuits deteriorate with age.

Lois collaborates on this project with Hong, as well as with Caltech biologist Kai Zinn, whose work uses *Drosophila* to determine how genes control the wiring of the brain.

"In mammals, the brain has a basic initial scaffold laid down by genetics, and then, over time, there is a lot of complicated experience-dependent rearrangement," Zinn says. "Fly brains, on the other hand, don't change much in response to experience, which makes them powerful models to understand how the intrinsic properties of neurons determine the synaptic connections they make."

DEVELOPMENT, FLIGHT, AND THE MICROBIOME

Drosophila research at Caltech is not limited to the fly's brain, however. Developmental biologist Angelike Stathopoulos examines fruit flies while they are still tiny bags of nuclei, before they have separated into individual cells. Within a few hours, a complex choreography of cellular differentiation will begin to form the pattern of the fly's body. Stathopoulos's group studies how genes trigger and orchestrate this developmental process and how they work together in a so-called gene regulatory network to do so.

Michael Dickinson sees *Drosophila* not so much as a simplified model for studying humans, but as a kind of paragon of efficiency that can shed light on the study of the biomechanics of flight in the same way that a cheetah would be the ultimate example for scientists studying running. He and his team have pioneered new techniques for recording signals from cells in the flies' brains as they navigate within an electronic flight simulator. As a fly steers itself within a simple virtual reality environment, the researchers use a fine glass electrode to record the activity of single neurons and also employ imaging techniques to watch the activity within specific regions of the fly's brain.

"It's best to understand the brain in real time while the organism is behaving as normally as possible," says Dickinson.

Microbiologist Sarkis Mazmanian and his colleagues primarily use mouse models to study the microbiome, the communities of bacteria that reside in the intestines of almost all animals, and how they affect the health and behavior of the whole organism. But, a few years ago, one of Mazmanian's graduate students examined the microbial communities in the tiny *Drosophila* gut, discovering that not only does the fly's microbiome keep its metabolism running smoothly, but it also influences the fly's locomotion. Indeed, flies without a microbiome exhibited the same erratic walking behaviors found in starving flies, even though these flies were well nourished.

"*Drosophila* offer an excellent model system to make rapid and detailed discoveries on a cellular and molecular level," Mazmanian says. "We are now investigating if the novel findings from flies translate to mammalian systems, like mice, to advance the research toward potential future applications in humans."

FULL CIRCLE

The fruit flies on Caltech's campus have been part of a long history of scientific discovery spanning fields across biology, engineering, and the social sciences, and stretching back to some of Caltech's earliest days.

Ruiz Sandoval feels both the pull of that history and the importance of the work today as she prepares the flies' healthy concoctions.

"Your days are very busy," she says of the process. "But it feels good when somebody gets recognition for their research, and you think, 'I had something to do with that. I made the fly food.'"

David Anderson is the Seymour Benzer Professor of Biology; the Tianqiao and Chrissy Chen Institute for Neuroscience Leadership Chair and the institute's director; and a Howard Hughes Medical Institute Investigator.

Michael Dickinson is the Esther M. and Abe M. Zarem Professor of Bioengineering and Aeronautics.

Elizabeth Hong (BS '02) is the Clare Boothe Luce Assistant Professor of Neuroscience.

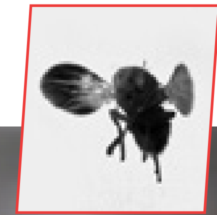
Carlos Lois is a research professor of neurobiology.

Sarkis Mazmanian is the Luis B. and Nelly Soux Professor of Microbiology and a Heritage Medical Research Institute Investigator.

Angelike Stathopoulos is a professor of biology.

Kai Zinn is the Howard and Gwen Laurie Smits Professor of Biology.

Anderson, Dickinson, Hong, Lois, Mazmanian, and Zinn are affiliated faculty members of the Tianqiao and Chrissy Chen Institute for Neuroscience at Caltech.



Aurora Ruiz Sandoval is in charge of making food for the fruit flies used in research in labs throughout the Division of Biology and Biological Engineering.

How Do Planets Take Shape?

A newly discovered mechanism helps explain planet formation, stellar winds, and more.

by Whitney Clavin

Caltech researchers have discovered a new mechanism to explain how the act of dust moving through gas leads to clumps of dust, which could explain everything from planet formation to outflows from stars, to the settling of volcanic ash. While dust clumps were already known to play a role in seeding new planets and many other systems in space and on Earth, how the clumps formed was unknown until now.

Phil Hopkins, Caltech professor of theoretical astrophysics, who carried out this work with Jonathan (Jono) Squire, a former postdoctoral fellow at Caltech, says that it was previously assumed that dust was stable in gas, meaning the dust grains would ride along with the gas without much happening, or they would settle out of the gas if the particles were big enough, as is the case with soot from a fire.

"What Jono and I discovered is that dust and gas trying to move with one another is unstable and causes dust grains to come together," says Hopkins. "Soon we began to realize that these gas-dust instabilities are at play anywhere in the universe that a force pushes dust through gas, whether the forces are stellar winds, gravity, magnetism, or an electrical field." The team's simulations show material swirling together, with clumps of dust growing bigger and bigger.

Perhaps the most notable implications for the newfound Hopkins-Squire instabilities are for the study of burgeoning planets. Planets take shape within dusty, rotating "protoplanetary" disks of gas and dust around young stars. In these disks, the dust coalesces to form bigger and bigger pebbles and boulders, then mountain-size chunks, and eventually full-grown planets.

At some point during this process, when the pieces of rock are big enough, about 1,000 kilometers in diameter, gravity takes over and smooshes the mountainous rocks into a round planet. The big mystery lies in what happens before gravity takes effect, that is, what is causing the dust particles, pebbles, and boulders to come together? Researchers once thought they might stick together in the same way dust bunnies accumulate under your bed, but there are problems with that theory.

"If you throw two pebbles together, they don't stick. They just bounce off each other," says Hopkins (pictured at right). "For sizes in between a millimeter and hundreds of kilometers, the grains don't stick. This is one of the biggest problems in modeling planet formation."

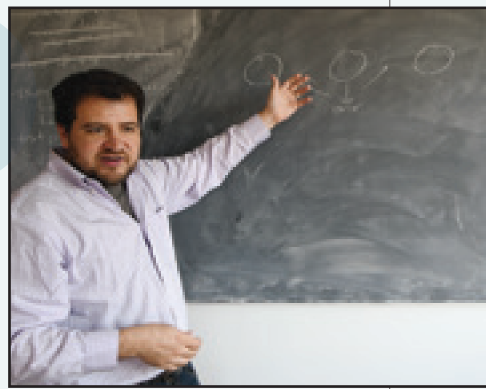
In the Hopkins-Squire instability model, which builds on previous models of dust-gas interactions, the formation of planetary dust clumps would begin with tiny dust grains moving through the gas orbiting in a protoplanetary disk. Gas would curl around a grain like river water around a boulder; the same thing would happen with another grain of dust nearby. These two gas flows might then interact. If there are many dust grains in relatively close proximity to one another, which is the case in planet formation, the net effect of the many resulting gas flows would be to channel the dust together into clumps.

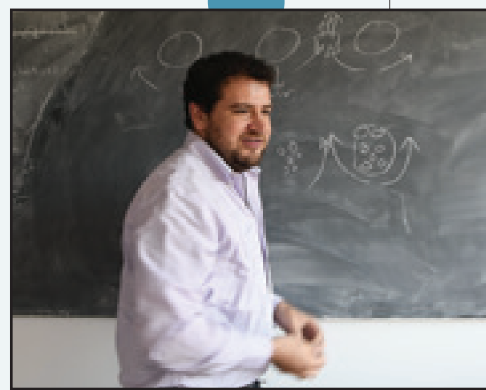
"In our new theory, this sticking through clumping can occur for a much wider range of grain sizes than previously thought, allowing smaller grains to participate in the process and rapidly grow in size," says Squire.

These instabilities may also be important in completely different situations here on Earth. For instance, volcanic ash or raindrops interact with our atmosphere in exactly the same way that astrophysical dust interacts with its surrounding gas.

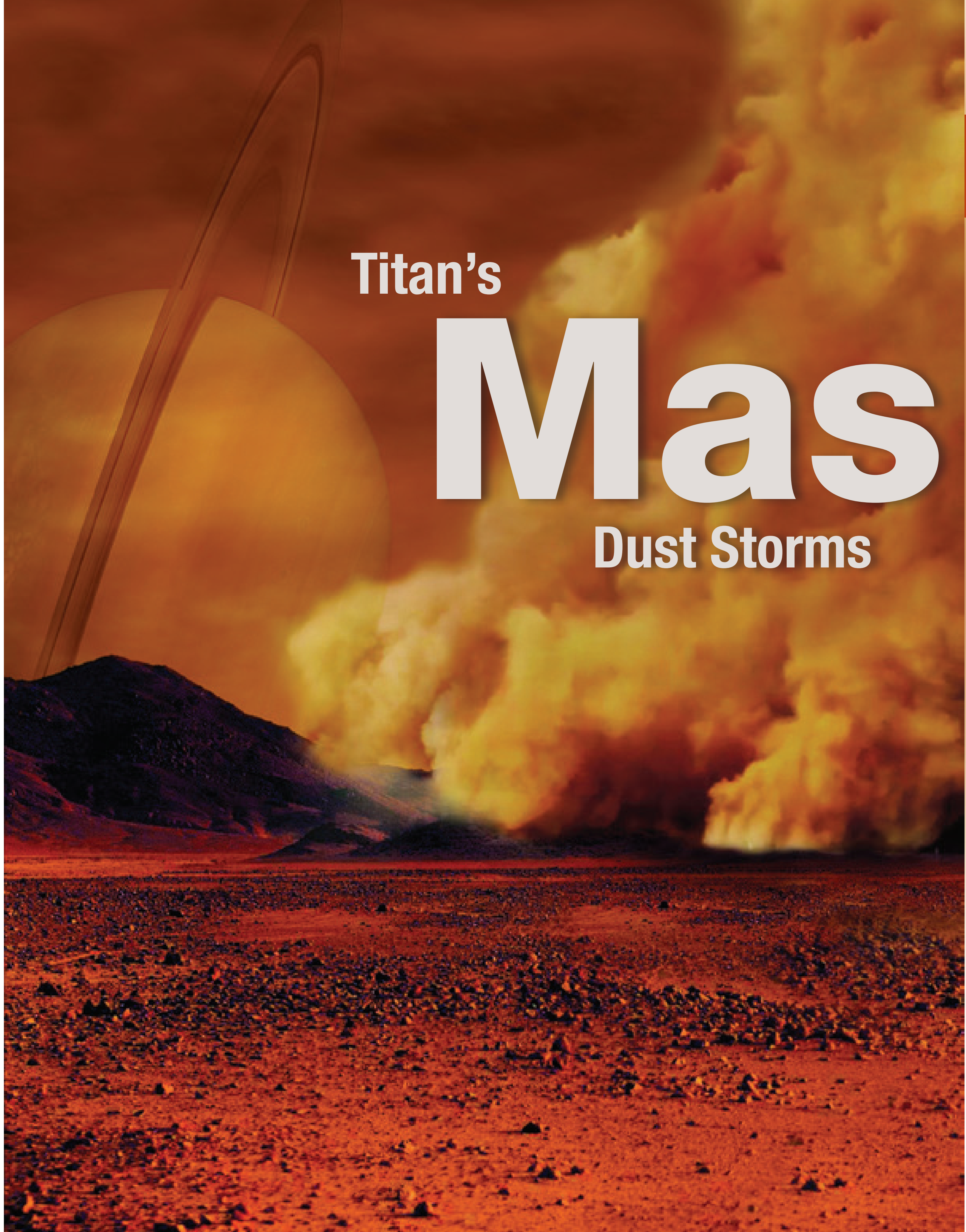
"It's very interesting to explore how these instabilities could operate in all these different scenarios," says Squire. "We're looking forward to understanding completely different instabilities in other areas of physics and applied mathematics and, hopefully, to finding other entirely new and interesting systems where this occurs." [C]

This research was funded by NASA and the National Science Foundation.





To watch a video about the Hopkins-Squire instability model, go to magazine.caltech.edu/post/planetshape



Titan's Massive Dust Storms

Data from NASA's Cassini spacecraft revealed in the fall of 2018 what appear to be giant dust storms in equatorial regions of Saturn's moon Titan. The discovery makes Titan the third solar system body, in addition to Earth and Mars, where dust storms have been observed.

"Titan is a very active moon," says Sébastien Rodriguez, an astronomer at the Université Paris Diderot in France and one of the lead researchers in this discovery. "We already know about its geology and exotic hydrocarbon cycle. Now we can add another analogy with Earth and Mars: the active dust cycle, in which organic dust can be raised from large dune fields around Titan's equator."

Titan is an intriguing world, in ways quite similar to Earth. In fact, it is the only moon in the solar system with a substantial atmosphere and the only celestial body other than our planet where stable bodies of surface liquid are known to still exist.

There is one big difference, though: on Earth such rivers, lakes, and seas are filled with water, while on Titan it is primarily methane and ethane that flow through these liquid reservoirs. In this unique cycle, the hydrocarbon molecules evaporate, condense into clouds, and rain back onto the ground.

The weather on Titan varies from season to season as well, just as it does on Earth. In particular, around the equinox (the time when the sun crosses Titan's equator) massive clouds can form in tropical regions and cause powerful methane storms. Cassini observed such storms during several of its Titan flybys.

When Rodriguez and his team first spotted three unusual equatorial brightenings in infrared images taken by Cassini around the moon's 2009 northern equinox, they thought they might be the same kind of methane clouds; however, an investigation revealed they were something completely different.

"From what we know about cloud formation on Titan, we can say that such methane clouds in this area and in this time of the year are not physically possible," says Rodriguez. The researchers were also able to rule out frozen methane rain or icy lavas. Modeling showed that the features must be atmospheric but still close to the surface and most likely forming a very thin layer of tiny solid organic particles. Since they were located right over the dune fields around Titan's equator, the only remaining explanation was that the spots were actually clouds of dust raised from the dunes.

Organic dust is formed when organic molecules, arising from the interaction of sunlight with methane, grow large enough to fall to the surface. "The near-surface wind speeds required to raise such an amount of dust as we see in these dust storms would have to be very strong," says Rodriguez. The existence of such strong winds generating massive dust storms implies that the underlying sand can be set in motion, too, and that the giant dunes covering Titan's equatorial regions are still active and continually changing.

Rodriguez notes that the winds could be transporting the dust raised from the dunes across large distances, contributing to the global cycle of organic dust on Titan and causing similar effects to those that can be observed on Earth and Mars. [C]

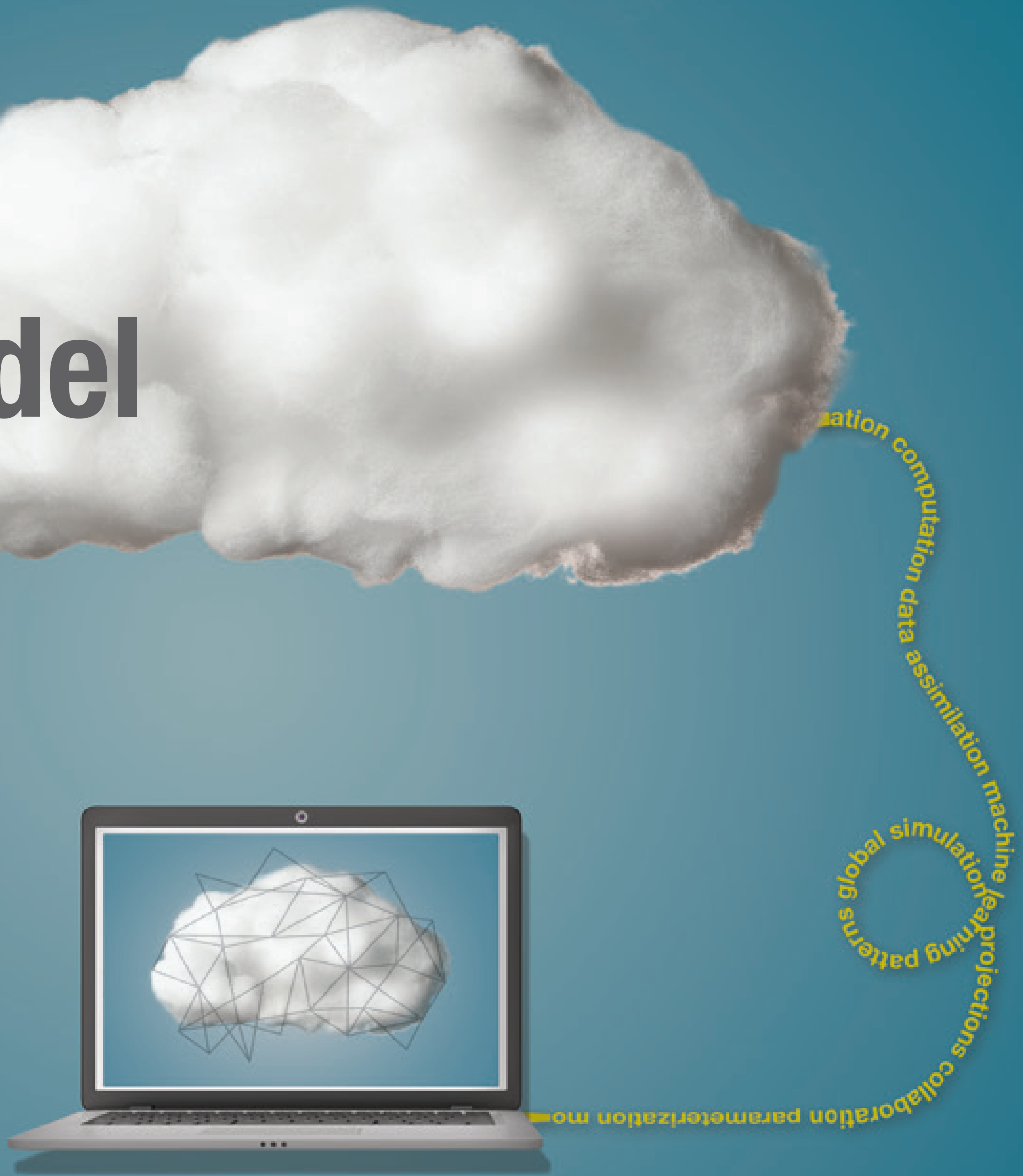
The results were obtained with Cassini's Visual and Infrared Mapping Spectrometer. The Cassini-Huygens mission is a cooperative project of NASA, ESA (European Space Agency), and the Italian Space Agency. The Jet Propulsion Laboratory is managed for NASA by Caltech; JPL manages the Cassini-Huygens mission for NASA's Science Mission Directorate in Washington. JPL designed, developed, and assembled the Cassini orbiter. The radar instrument was built by JPL and the Italian Space Agency, working with team members from the U.S. and several European countries. The Cassini spacecraft deliberately plunged into Saturn on September 15, 2017, ending its nearly 20-year mission.

For more information about Cassini, visit **nasa.gov/cassini** and **saturn.jpl.nasa.gov**

A Model Climate

Computer models hold the key to understanding our climate and predicting its future. Researchers from across the country are on a quest to improve those models.

by Robert Perkins



When it comes to climate change, one thing is certain, says Caltech climate scientist Tapio Schneider: "Global warming is upon us. Earth has warmed 1.8 degrees Fahrenheit over the past century. This warming is consistent with what basic physics tells us we should expect, given the accumulation of human greenhouse gas emissions in the atmosphere."

The question, then, is not whether but *how much* the earth will be warming and how fast. For these projections, researchers rely on computer models to generate how-and-when scenarios.

"Projections with current climate models, such as how features like rainfall extremes will change, still have large uncertainties, and the uncertainties are poorly quantified," says Schneider. "For cities planning their stormwater management infrastructure to withstand the next 100 years of floods, this is a serious issue; concrete answers about the likely range of climate outcomes are key for planning."

Making predictions more accurate is important for reasons ranging from economic to environmental. As cities contemplate building seawalls to protect against rising ocean waters and farmers attempt to determine what to plant to cope with shifting precipitation patterns, everyone needs improved climate predictions.

"Caltech's effort in climate modeling comes at a critical time in the history of climate science," says John Grotzinger, chair of Caltech's Division of Geological and Planetary Sciences. "Current models diverge significantly in their predictions of future warming. The question is how we can achieve greater accuracy in predictions."

Where does all the uncertainty in the models come from? Scientists say it is the result of lack of computing power both to resolve fine details of the climate system, such as the turbulent dynamics of clouds, and to systematically integrate observations of, for example, clouds and ecosystems into models.

Building a better model

Facing the certainty of a changing climate coupled with the uncertainty that remains in predictions of *how* it will change, scientists and engineers from across the country are teaming up to build a new type of climate model that is designed to provide more precise and actionable predictions.

The comprehensive effort capitalizes on the vast amounts of data that are now available and on increasingly powerful computing capabilities both for processing data and for simulating Earth's system.

The new model will be built by a consortium of researchers led by Caltech in partnership with MIT; the Naval

Postgraduate School (NPS); and JPL, which Caltech manages for NASA. The consortium, dubbed the Climate Modeling Alliance (CliMA), plans to fuse Earth observations and high-resolution simulations into a model that represents important small-scale features, such as clouds and turbulence, more reliably than existing climate models. The goal is a climate model that projects future changes in critical variables such as cloud cover, rainfall, and sea-ice extent with uncertainties at least two times smaller than existing models.

Cloudy data

Current climate modeling relies on dividing up the globe into a grid and then computing what is happening in each sector of the grid as well as how the sectors interact with one another. The accuracy of any given model depends in part on the resolution at which the model can view the earth; that is, the size of the grid's sectors. Limitations in available computer processing power currently mean that those sectors generally cannot be any smaller than tens of kilometers per side.

Those might seem small on a global scale but, for climate modeling, the devil is in the details: details that get missed in a too-large grid.

For example, low-lying clouds, like those you might find over the Pacific off the coast of California, are especially important for regulating Earth's temperature (in part, by reflecting sunlight), as anyone who has experienced a cool overcast day in spring knows. They do this in part by reflecting sunlight, but they are so small that they fall through the cracks of existing models.

Similarly, changes in Arctic sea ice have been linked to wide-ranging effects on everything from polar climate to drought in California. But it is difficult to predict how that ice will change in the future because it is sensitive to the density of cloud cover above and the temperature of ocean currents below, neither of which can be resolved by current models.

With the temperature rising and the clock ticking down, a new strategy is needed, one that involves new thinking about how to fuse climate models with the massive amounts of data being generated today.

Zooming in

To capture the large-scale impact of these small-scale features, the team will use high-resolution simulations that model the features in detail in selected regions of the globe. Those simulations will be nested within the larger climate model. The effect will be a model capable of "zooming in" on selected regions, providing detailed local climate information about those areas and informing the modeling of small-scale processes everywhere else.

"The ocean soaks up much of the heat and carbon accumulating in the climate system. However, just how much it takes up depends on turbulent eddies in the upper ocean, which are too small to be resolved in climate models," says Raffaele Ferrari, Cecil and Ida Green Professor of Oceanography at MIT. "Fusing nested high-resolution simulations with newly available measurements from, for example, a fleet of thousands of autonomous floats could enable a leap in the accuracy of ocean predictions."

Existing models are often tested by checking predictions against observations. "But that system only works to the degree that a human then goes in and fixes the model based on their best understanding of the system," Schneider says.

To accelerate and expand the cycle of fusing data with models, Schneider is working with Caltech computational scientist Andrew Stuart. The new model will use data-assimilation and machine-learning tools to train the model to improve itself in real time, harnessing both Earth observations and the nested high-resolution simulations.

"The success of computational weather forecasting demonstrates the power of using data to improve the accuracy of computer models; we aim to bring the same successes to climate prediction," says Stuart.

"The success of computational weather forecasting demonstrates the power of using data to improve the accuracy of computer models; we aim to bring the same successes to climate prediction."
—Andrew Stuart

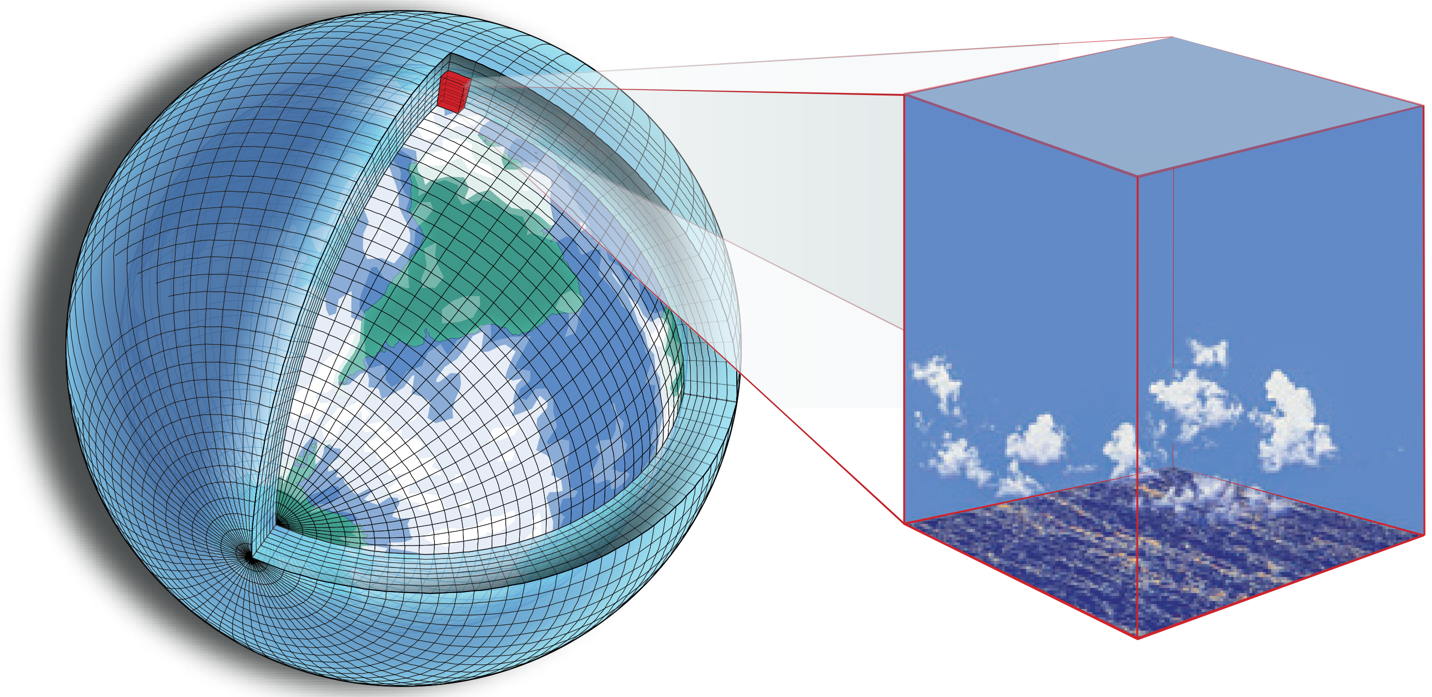
"The topic requires collaboration across traditionally disparate disciplines," Schneider adds, "and what we are doing with Andrew is a good example of how this works well at Caltech."

Each of the partner institutions brings a different strength and research expertise to the project. At Caltech, Schneider and Stuart will focus on creating the data-assimilation and machine-learning algorithms as well as models for clouds, turbulence, and other atmospheric features. At MIT, Ferrari and John Marshall, also a Cecil and Ida Green Professor of Oceanography, will lead a team that will model the ocean, including its large-scale circulation and turbulent mixing. At NPS, Frank Giraldo, professor of applied mathematics, will lead the development of the computational core of the new atmosphere model in collaboration with fellow researchers Jeremy Kozdon and Lucas Wilcox. At JPL, a group of scientists will collaborate with the team on campus to develop process models for the atmosphere, biosphere, and cryosphere.

The consortium will operate in a fast-paced, start-up-like atmosphere and hopes to have the new model up and running within the next five years, an aggressive timeline for building a climate model essentially from scratch.

"A fresh start gives us an opportunity to design the model from the outset to run effectively on modern and rapidly evolving computing hardware, and for the atmospheric and ocean models to be close cousins of each other, sharing the same numerical algorithms," says Giraldo.

"The goal for us is to get ahead of the unnatural experiment we are currently conducting with the climate system," adds Schneider, "to provide accurate and actionable climate predictions before the climate system has revealed the answer to the question of how it will change, and before it is too late to mitigate that change and adapt to it efficiently."



Climate models divide Earth's surface and atmosphere into grid boxes within which temperatures, winds, and ocean currents are computed. Like pixels in an image, the smaller these individual boxes, the clearer and more accurate the model they ultimately create. Clouds are too small to be resolvable in global models, but they can be resolved in high-resolution simulations in limited areas.

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John Grotzinger, the Fletcher Jones Professor of Geology, is also the Ted and Ginger Jenkins Leadership Chair in the Division of Geological and Planetary Sciences.

Tapio Schneider is Caltech's Theodore Y. Wu Professor of Environmental Science and Engineering and senior research scientist at JPL.

Andrew Stuart is the Bren Professor of Computing and Mathematical Sciences.

Funding for this project is provided by the generosity of Eric and Wendy Schmidt (by recommendation of the Schmidt Futures program); Mission Control Earth, an initiative of Mountain Philanthropies; Paul G. Allen Philanthropies; the Heising-Simons Foundation; Blaine and Lynda Fetter; Deborah Castleman; Caltech trustee Charles Trimble; the Chair's Council of the Division of Geological and Planetary Sciences; and the National Science Foundation. More information can be found at https://clima.caltech.edu.

BUILDING KECK

An Oral History

Between 1991 and 1992, the Caltech Archives conducted a series of seven oral history interviews with administrators, designers, astronomers, and managers from Caltech and the University of California (UC) to record the history and development of the W. M. Keck Observatory. Those interviews were published online for the first time in the fall of 2018.

Construction on the first of the two Keck telescopes began in September 1985 after a $70 million donation from the W. M. Keck Foundation; the Keck I telescope's first light occurred a little more than five years later, in late 1990. At the time of the interviews, a second Keck Foundation donation had made it possible to begin construction of the Keck II telescope, which would capture first light in October 1996.

To tell the Keck story, *Caltech* magazine turned to those oral histories, weaving one narrative from seven storytellers. The entire set of interviews may be found on the website of the Caltech Oral History Project. This is the first in a series of articles on the past, present, and future of the Keck Observatory and the science done there that will appear in Caltech's print and online publications.

THE STORYTELLERS
(in alphabetical order)

William Frazer, professor of physics at UC Berkeley, emeritus, UC's senior vice president for academic affairs during the construction of Keck I.

Jerry Nelson (BS '65) (1944–2017), project scientist for the W. M. Keck Observatory from 1985 through 2012, and principal designer of the 10-meter segmented mirrors for which Kecks I and II are known.

Gerry Neugebauer (PhD '60) (1932–2014), Caltech's Robert Andrews Millikan Professor of Physics, Emeritus, who played a key role in design and construction of Keck 1 as chair of the Division of Physics, Mathematics and Astronomy.

J. Beverley Oke (1928–2004), Caltech professor of astronomy, emeritus, who designed many of the instruments for Keck I.

Wallace L. W. Sargent (1935–2012), Caltech's Ira S. Bowen Professor of Astronomy, who had worked as director of Palomar Observatory and was involved, along with several others at Caltech, in working with the Keck Foundation to finance what would become the Keck I telescope.

Maarten Schmidt, Caltech's Francis L. Moseley Professor of Astronomy, Emeritus, who helped decide upon the segmented-mirror design created by Jerry Nelson for the Keck telescopes.

Gerald Smith, formerly with JPL, who was the project manager for the W. M. Keck Observatory's telescopes from the beginning of the project until his retirement in 1996, soon after the dedication of Keck II.

THE BEGINNING:

"Here's how you weld."

Frazer: In '83, David Gardner became president [of the UC system] and … I became the university's principal administrator on the telescope project.

Neugebauer: I was fairly deeply involved in the beginning. I was the director of Palomar, and I basically took two years off to run IRAS [InfraRed Astronomical Satellite]. And when I came back from that, there was a question: "What should we do?"

Nelson: I met [Gerry] Neugebauer and [Robert] Leighton, my TAs as a sophomore [at Caltech], and they invited me to work for them. It turned out that they were involved in infrared astronomy, and in particular, they were involved in building a 60-inch telescope to do an infrared sky survey on Mt. Wilson. … They were going to build everything themselves with a spun epoxy mirror, and they got me involved in practically every aspect of designing and building this thing. I remember the day they hired me. Leighton dragged me into the shop and walked me into one of the rooms and said, "OK, see all these bars of steel? I want them all welded together, and here's how I want them done." And he pulled out a welding torch and he said, "Here's how you weld." He gave me a five-minute lesson and said, "Here." *[Laughter]*

Oke: We already … had the biggest telescope in the world, and we thought we were doing about as good a thing with it as anybody could. But I think we also realized … that we needed more "oomph," we needed more collecting area, if we were going to really keep up … our leadership role in astronomy.

Sargent: I wrote a memo to [Jack] Roberts [who was then Caltech's provost] on the 18th of March, 1980, in which I said, "It's now thought to be technically possible to construct ground-based optical telescopes in the 10-to-15-meter range, using thin, segmented primary mirrors and active optics. There are plans to construct such telescopes by the late 1980s. One of these schemes, a 10-meter telescope, is being pushed by the University of California, with some input … from Caltech." We actually had a few advisers on their scheme. "We should seriously consider becoming a major partner in the UC scheme if we are not to fall behind in the late 1980s."

Upper left: Jerry Nelson (far right) and friends appear atop a full-sized prototype of the supporting frame for a mirror segment. Right: The Keck telescopes atop Maunakea.

PARTNERING:

"Having the money is all the difference."

Schmidt: Caltech was asked [by UC] whether we wanted to be a one-quarter partner, which started things on a very much more definitive course.

I think it was sometime in August 1984, or soon thereafter, we essentially settled on three scenarios of how things could be handled. And one would be that while we would build the telescope on Maunakea, the University of California would find enough money to build one in the Southern Hemisphere, and there would be cooperation, and the design would be the same. The second option was that, near the [Keck] telescope on the same mountain, another one might be built by the University of California, and [we] would do interferometry between the two and further cooperate. And a third option essentially came down to this, Caltech would provide the funds to build the telescope, and the University of California would bring in enough funds to run the installation for a considerable time, which turned out to be 25 years. Well, as we know, the final option was the one that became operative.

Smith: When the Keck Foundation and Caltech came in, I saw this as a real positive development, because I felt that the entry of Caltech would make it a much stronger operation. The funding was, of course, the key thing; having the money is all the difference.

So Caltech just breathed new life into it, as far as I was concerned.

WHERE TO PUT THE TELESCOPE?

"Or you can go to an island."

Neugebauer: The sites that are good for astronomy turn out to be sites that are high, or near water, so you have very smooth air flowing over it. That's why the good sites are here in California [and] in Chile. Or you can go to an island, and you have the wind blowing over the island in a nice smooth way.

Sargent: There'd been telescopes [on Maunakea] since … the late '60s.

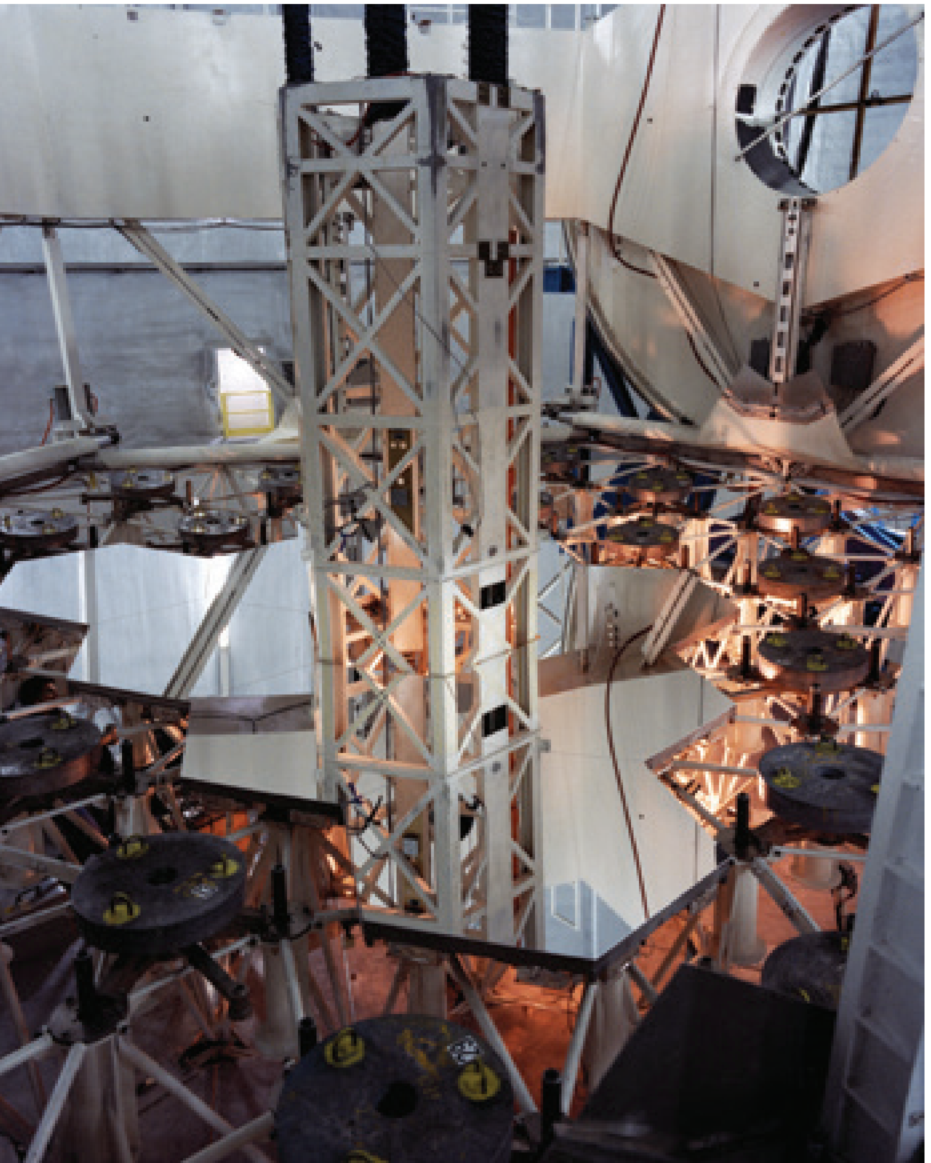
Schmidt: At that time, the University of California people, I think, had already settled on Maunakea, and we liked that very much: almost no light pollution, very high, and so on.

SOLVING PROBLEMS:

"It's a very clever idea."

Sargent: There were two competing designs [for the mirror], over which they had a shootout. One design was to have a single, very thin piece of glass that was flexible, the so-called rubber mirror, and adjust it with active controls from the back. The other was [Jerry] Nelson's idea, which was to have a segmented mirror in which there would be 36 hexagonal solid pieces which would be adjusted, but you wouldn't adjust the whole. It wouldn't be a complete surface; there would be cracks in it.

Nelson: In 1980 [or] probably the end of '79, when this committee was going to meet, there was a group of six or seven people on this committee, and we presented reports to them, both written and oral. … And after they reviewed it and talked to us at length, they ended up saying the segmented-mirror telescope was the way to go.



Early on, not knowing much about how you fabricate optics, I just sort of thought you take these off-axis mirrors and you get them polished somehow. And as I looked into that, I realized that, "No, wait a minute, polishing is not like machining metal. It's an art, not a science or even a craft." *[Laughter]* And I'd talked to people who'd polished optics, and they said, "Oh, no. We don't know how to do that. That's hard." … And I realized that this was a real issue, this wasn't a minor matter that we could solve someday in the future. It was a fundamental stumbling block, just as important as the active-control system.

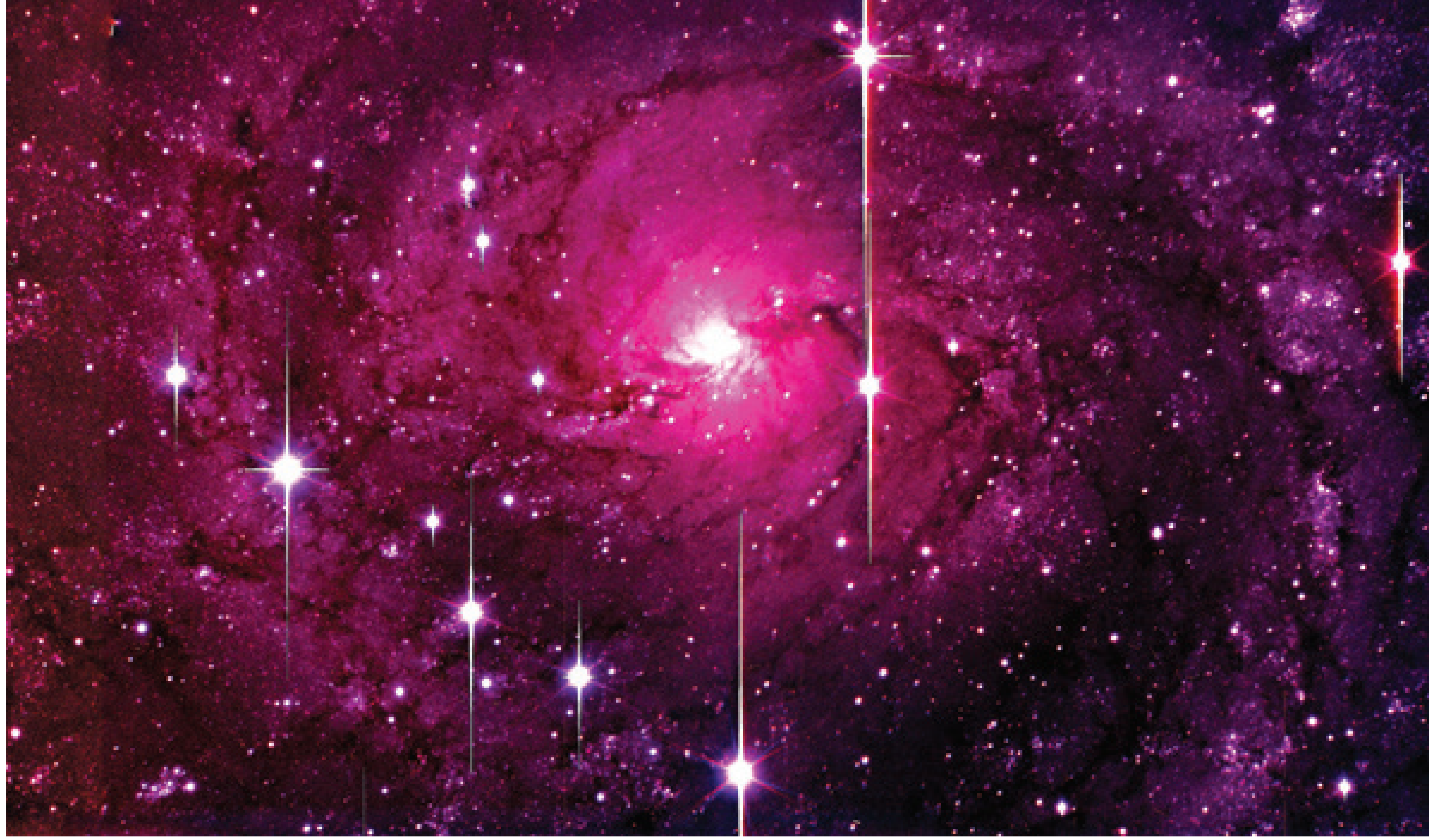
Neugebauer: How do you make 1.8-meter mirrors inexpensively? Basically, the mirrors have to be in the form of a parabola after they're assembled. But it's much easier to polish them as spheres. So, what you do is you take the piece of glass and "stress polish" it. You bend the glass with weights along the edges, in just the right shape, [and] you polish that into a sphere. Then, when you release the weights, it springs back to the right shape. It's a very clever idea. It was Jerry Nelson's idea. That has turned out to work.

[Another] big technical problem, which turned out to work relatively easily, was to make all the mirrors play together. That was demonstrated on nine mirrors; they could make nine mirrors all point together and act as if they were one big mirror.

Nelson: When I did the calculations, I realized that with segments, you put them on some kind of structure. It's going to deform by such a large amount that there's no way you can just position them carefully and they'll stay where they belong. … I realized we were going to have to have some sort of active-control system.

Schmidt: The thing that struck me as something that went particularly well was the alignment system of the segments. That was, I think, only first tested just a little under a year ago, last March or April 1990 or so, close to first light. And when that system was turned on to align the first nine segments, the noise in the alignment was on the order of 15 nanometers, whereas when the dome was rotating, it became on the order of 40, and that was the first result, which was well within the requirements. And that's remarkable, because people in the community who had been following all this had been most worried about, or critical of, the claims made by Jerry Nelson that you can align these segments and then it's as good as if it were one surface. … Now that doesn't mean that it's easy. *[Laughter]* Jerry Nelson somehow did it particularly well.

Left: Nine of Keck's segmented mirrors. Upper right: Galaxy UGC 2847 as seen by Keck.



And then, the development of lightweight mirrors … opened the possibility of having telescopes that were very considerably cheaper per unit area than they used to be, by a factor of probably 5 to 10 or so. … I'm sure that otherwise the Keck Telescope would have cost between a half billion and a billion dollars or so.

WHAT'S NEXT?

"That's where the Keck, I think, will be priceless."

Oke: Well, the first things we will do when we put on the spectrograph, which we're designing, are pretty simple things. We'll take pictures that are pretty, obviously, spectacular. [They are] nice to look at. … They'll be just single objects initially, or a galaxy sitting on a single slit. And then as things start to get working better and better, you try long-slit kinds of things, and then you start multi-slit things, and then you try fainter and fainter things.

Schmidt: That's where the Keck, I think, will be priceless. It will really allow us to do things with distant galaxies that you now wouldn't think of.

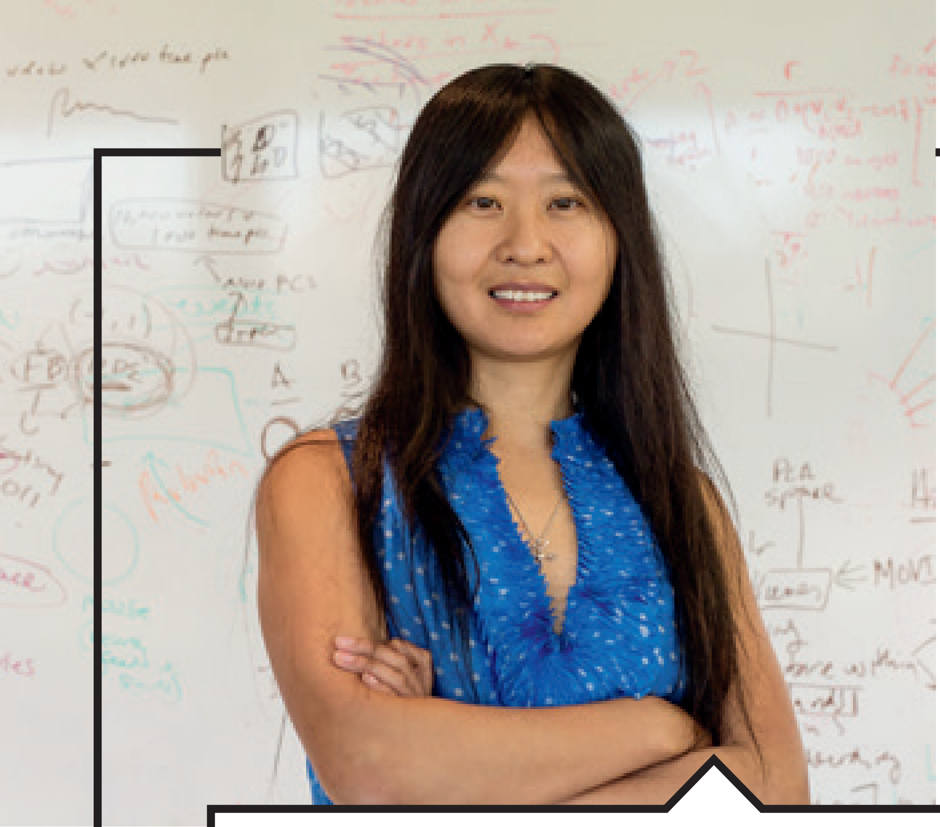
Neugebauer: I would try and look at the center of the ultra-luminous galaxies. There are a series of galaxies that have a hundred to a thousand times more energy than the galaxies we know about. I would try to look at those and really study what makes them tick.

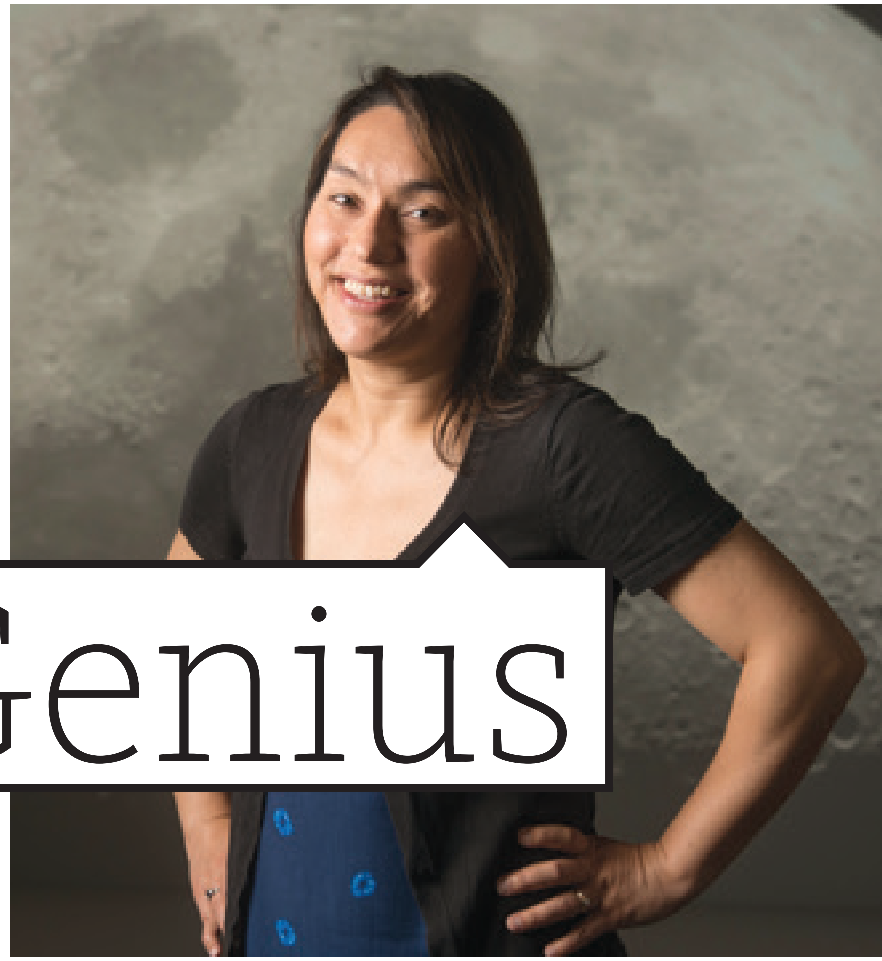
Oke: The second Keck has always been sitting there as a possibility. I don't know, for instance, whether this second telescope was something [Howard] Keck had talked about. But the rumors were around that he had talked a bit about the possibility of there being two. And in the early UC combination, there was talk about two. So this idea of a second Keck had always been in the deep background.

Nelson: It has sure been an interesting project. [C]

The W. M. Keck Observatory is home to the world's most scientifically productive optical and infrared telescopes. The Keck I telescope began its scientific observations in May 1993; Keck II saw first light in October 1996. Each telescope weighs 300 tons and operates with nanometer precision; each has a primary mirror composed of 36 hexagonal segments that work in concert as a single piece of reflective glass. The observatory was made possible by the financial support of the W. M. Keck Foundation.

Expert opinion from Caltech's newest MacArthur Fellows





Ask a Genius

Every year, the John D. and Catherine T. MacArthur Foundation awards unrestricted fellowships, so-called Genius Grants, to individuals who show extraordinary originality and dedication in their creative pursuits. The 2018 class of fellows includes two Caltech alumnae, Doris Tsao (BS '96) and Sarah Stewart (PhD '02).

Doris Tsao, Caltech professor of biology, T&C Chen Center for Systems Neuroscience Leadership Chair and Director, and Howard Hughes Medical Institute Investigator, was recognized for her work studying the neural mechanisms underlying primate vision. In 2017, Tsao and her team discovered the system the brain uses to recognize facial identity.

Sarah Stewart, a professor in the Department of Earth and Planetary Sciences at the University of California, Davis, won the award for her work exploring how celestial collisions give rise to planets and their natural satellites, such as the earth and moon.

Recently, *Caltech* magazine asked members of the community what questions they had for the pair. Tsao (above left) and Stewart were kind enough to take some time away from their award-winning research to give us their answers.

Q + A

How has your experience at Caltech inspired your success?

Sarah Stewart: A wise faculty member told me that it is better to be right than to be first. I learned that I didn't have to play the game of rushing my work out the door and that in the end it would be better if I thought deeply about problems.

What was the most important lesson you learned at Caltech?

Doris Tsao: There are no boundaries between fields: nature is a beautiful whole structure that we need to study from many angles. The Caltech Core Curriculum instilled that idea in me. It's why I protested when the proposal was made to abolish the two-year physics requirement for undergrads on the grounds that "quantum mechanics is not relevant for biology majors." My own research on the biology of vision is inspired by insight into dynamical systems and representations of symmetry that come from math and physics.

SS: I learned about imposter syndrome during my first year at Caltech… from a flyer on the wall in my building. I had never heard this term before, so I looked it up. The realization that EVERYONE felt this way was a huge factor in my self-confidence in graduate school.

How do you hope your research will impact the world?

DT: Many of us have a sense of being trapped within ourselves, and we alleviate it in different ways: by making friends or going for a walk outside. For me, understanding the brain and how it generates all of our perceptions, thoughts, and actions will be the greatest liberation.

SS: I want to nurture and expand the public's appreciation of the wonders of nature. I like to point out that nature has a bigger imagination than we do, which is why we always find something unexpected when we do something new, such as sending spacecraft to a new planet or developing new telescopes. My work on the origin of the moon led to the discovery of a completely new type of planetary object: a huge, vaporized body that we named a synestia.

How will receiving this fellowship enhance your research?

SS: I don't know yet! I have not decided what to do with it, and I am going to take my time to consider different options.

DT: The MacArthur is the anesthetic for the last 10 grant rejections I got (and the next 10 that I will get), and a wonderful surprise.

What are you going to do with the award money? Are there any personal pleasures you're hoping to indulge in?

SS: My personal goal is to use the fellowship to do something new that I would not have done otherwise. I want it to be a mix of personal and professional activities. (Yes, taking the family on world travels is on the list.)

DT: I haven't yet calculated if it will cover my one-year-old boys' day-care tuition until they get to elementary school. Maybe there will be a little left over for a nice lunch at Ernie's.

What do you think of the word "genius" and what it means?

DT: To me, a genius is someone who follows an idea sparked by some light in their own mind, which is not obvious yet to anyone, and might not be even after the first few tries at explanation, because it is still before its time. A genius tends to live in the realm of possibility. They don't care if their fruits can be sold at the market; in fact, they know they can't because no one else can see them. Yet, they persist in applying the full rigors of creative hard work to carry their idea forward to its logical implications. Three examples of genius from my field of neuroscience: Julian Jaynes's neurological-anthropological exploration of the origin of consciousness; Donald Mackay's proposal for how a robot can learn new concepts not programmed by its maker; and Henri Poincaré's analysis of the origin of our subjective notion of space.

SS: Genius is such an intimidating word to me. I very much resonate with the MacArthur Fellowship's emphasis on creativity. I have been thinking a lot about creativity and how to teach students to develop their own creative activities. Creativity can be learned and honed.

As alumnae, what advice would you give to Caltech students today?

DT: Follow your curiosity and be irresponsibly optimistic about the future!

SS: Talk to your professors! They are amazing people. Caltech's faculty are its most valuable resource.

When did you know you wanted to be a scientist?

DT: I knew from a very young age. I liked to read biographies, and the most glorious heroes to me were the scientists and composers.

SS: My amazing high school physics teacher, Eric Curry, made me want to study physics in college. He had the magic touch of teaching: clear explanations mixed with sheer fun.

Why does the office printer always get jammed?

DT: Because people are always making peanut butter and jam sandwiches on it?

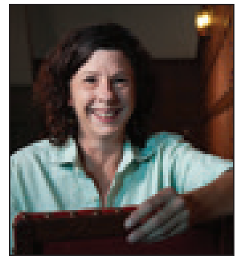
SS: Because it knows I need to teach in five minutes.

In Memoriam

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

Harold Brown 1927–2019

Harold Brown, who was Caltech president, emeritus; life member of the Caltech Board of Trustees; and former secretary of the U.S. Department of Defense (DOD), passed away on January 4. He was 91 years old. During Brown's presidency (1969–77), he made significant changes to the undergraduate curriculum, developed a campus master plan, and paved the way for women to be admitted to Caltech (in 1970).

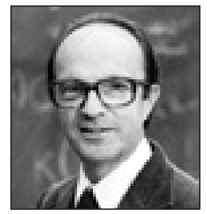


Fiona Cowie 1963–2018

Fiona Cowie, professor of philosophy at Caltech, passed away on December 9 at the age of 55. She joined Caltech in 1992 as an instructor in philosophy and was appointed assistant professor in 1993, associate professor in 1998, and professor in 2010. Cowie's research explored the evolution of the human mind and philosophical questions about language. She was a proponent of the theory that language is not an innate product of the human brain but is instead a technological innovation.

Walter Burke 1922–2018

Walter Burke, longtime president and treasurer of the Sherman Fairchild Foundation and a life member of the Caltech Board of Trustees, passed away on November 1. He was 96 years old. First named to the Caltech Board of Trustees in 1975, Burke was elected a life member in 2009. In 2014, Caltech and the Sherman Fairchild Foundation honored Burke with the creation of the Walter Burke Institute for Theoretical Physics.



Wilhelmus A. J. Luxemburg 1929–2018

Wilhelmus Luxemburg, emeritus professor of mathematics at Caltech, passed away on October 2. Luxemburg joined Caltech in 1958, becoming full professor in 1962, a position he held until 2000. Luxemburg's most notable work was in the theory of Riesz spaces (partially ordered vector spaces where the order structure is a lattice) and infinitesimals (entities too small to be measured).

Endnotes

If you won a MacArthur award, what would you use the money to do, create, or explore?

I will use it to create the world's smallest and most user-friendly continuous glucose monitor to help more than 420 million diabetes patients live a productive and positive life.

Muhammad Mujeeb-U-Rahman (PhD '14)
IRVINE, CA

I would develop a fleet of drones with high-resolution video that would be launched in major West Coast cities in the event of an earthquake.

Tom Heaton (PhD '79)
PASADENA, CA

An augmented reality system that pinpoints small foreign objects (e.g., glass splinters) inside a human body and helps to extract them quickly during a surgery.

Ivan Grudinin (PhD '08)
PASADENA, CA

I would create a miniature rocket to launch geology samples off of Mars.

John Whitehead (BS '81)
DAVIS, CA

Chances are I'd be in the midst of some exciting research, in which case I'd use the money to get rid of many duties of being an academic and just FOCUS, FOCUS, FOCUS. Learning is a great joy and one that we sometimes give up to run a research program.

Joel Bowman (PhD '74)
ATLANTA, GA

I would use the money to support a graduate or postdoctoral fellowship or research grant targeting specifically STEM parents (particularly but not limited to women) who may have suffered hardship while balancing their work with parenting duties.

Vivian U (BS '06)
LA HABRA HEIGHTS, CA

I would use the money to look into the safety (or danger) provided by the older flood control dams in Southern California. Particularly, evaluate their vulnerability to debris flows.

Robert Tait (BS '62)
PASADENA, CA

My passion in these, my later years, is science education. If only everyone in the world had a proper education, especially in science, then many of today's problems would not exist. With the money and recognition from a MacArthur award I would be able to reach more students with online science lessons using real experiments and hands-on measurements.

Harry Keller (BS '63)
MANHATTAN BEACH, CA

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And remember to get social:

For more Endnotes responses, go to magazine.caltech.edu/post/endnotes4

I would spend at least a year examining the Caltech archives looking at the unpublished work of John Todd and Olga Taussky-Todd for research they did on the Frobenius-Taussky-Zassenhaus theorem.

Nicomedes Alonso (BS '82)
MOORHEAD, MN

Caltech magazine

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Helping the Blind to Navigate

Soon, the blind might have some help navigating unfamiliar spaces, thanks to Markus Meister (PhD ’87), Anne P. and Benjamin F. Biaggini Professor of Biological Sciences, who, along with his colleagues, has combined augmented reality hardware and computer vision algorithms to develop software that translates the optical world into plain English audio that is delivered through a portable headset. The device could one day be offered by places like banks, shopping malls, hotels, and museums.

Find out more at
magazine.caltech.edu/post/blindnav